An introduction to Magnets for Accelerators

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CERN

John Adams Institute
Accelerator Course

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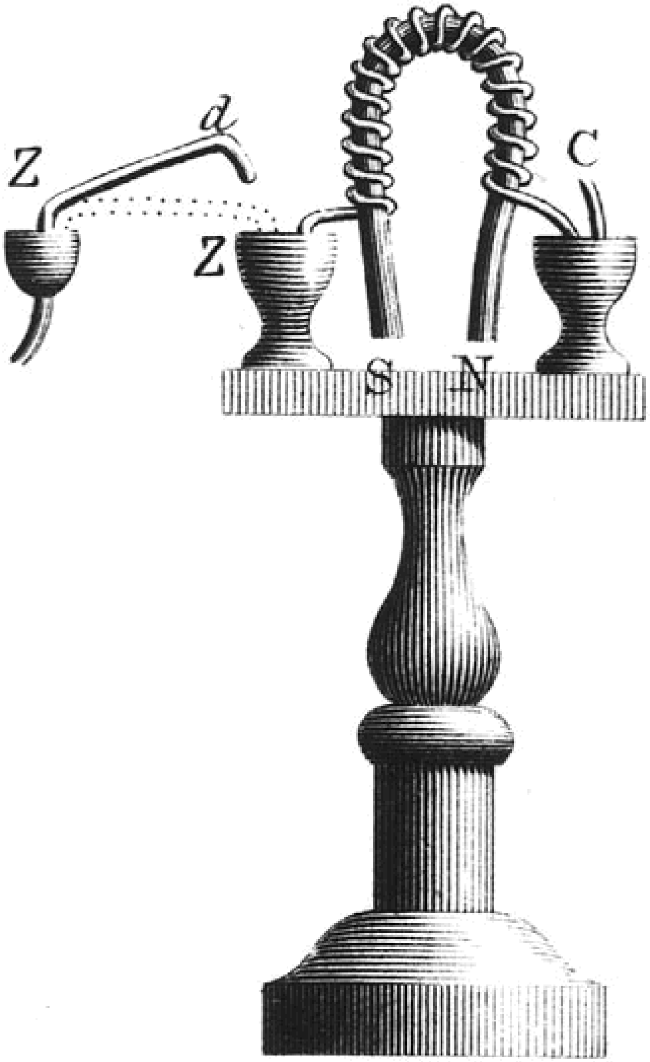
This is an introduction to magnets as building blocks of synchrotrons / transfer lines

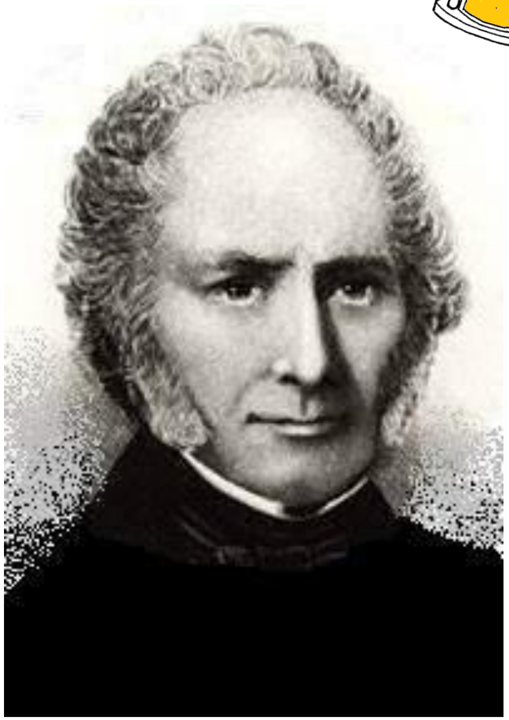
```
//
// MADX Example 2: FODO cell with dipoles
// Author: V. Ziemann, Uppsala University
// Date: 060911

TITLE,'Example 2: FODO2.MADX';

BEAM, PARTICLE=ELECTRON,PC=3.0;

DEGREE:=PI/180.0;

QF: QUADRUPOLE,L=0.5,K1=0.2;
QD: QUADRUPOLE,L=1.0,K1=-0.2;
B: SBEND,L=1.0,ANGLE=15.0*DEGREE;

FODO: SEQUENCE,REFER=ENTRY,L=12.0;
  QF1:   QF,      AT=0.0;
  B1:    B,       AT=2.5;
  QD1:   QD,      AT=5.5;
  B2:    B,       AT=8.5;
  QF2:   QF,      AT=11.5;
ENDSEQUENCE;
```

If you want to know more…

1. N. Marks, Magnets for Accelerators, JAI (John Adams Institute) course, Jan. 2015
2. D. Tommasini, Practical Definitions & Formulae for Normal Conducting Magnets
3. Lectures about magnets in CERN Accelerator Schools
4. Special CAS edition on magnets, Bruges, Jun. 2009
5. Lectures about magnets in JUAS (Joint Universities Accelerator School)
6. Superconducting magnets for particle accelerators in USPAS (U.S. Particle Accelerator Schools)
7. J. Tanabe, Iron Dominated Electromagnets
8. P. Campbell, Permanent Magnet Materials and their Application
9. K.-H. Mess, P. Schmüser, S. Wolff, Superconducting Accelerator Magnets
10. M. N. Wilson, Superconducting Magnets
11. A. Devred, Practical Low-Temperature Superconductors for Electromagnets
12. L. Rossi and E. Todesco, Electromagnetic design of superconducting dipoles based on sector coils

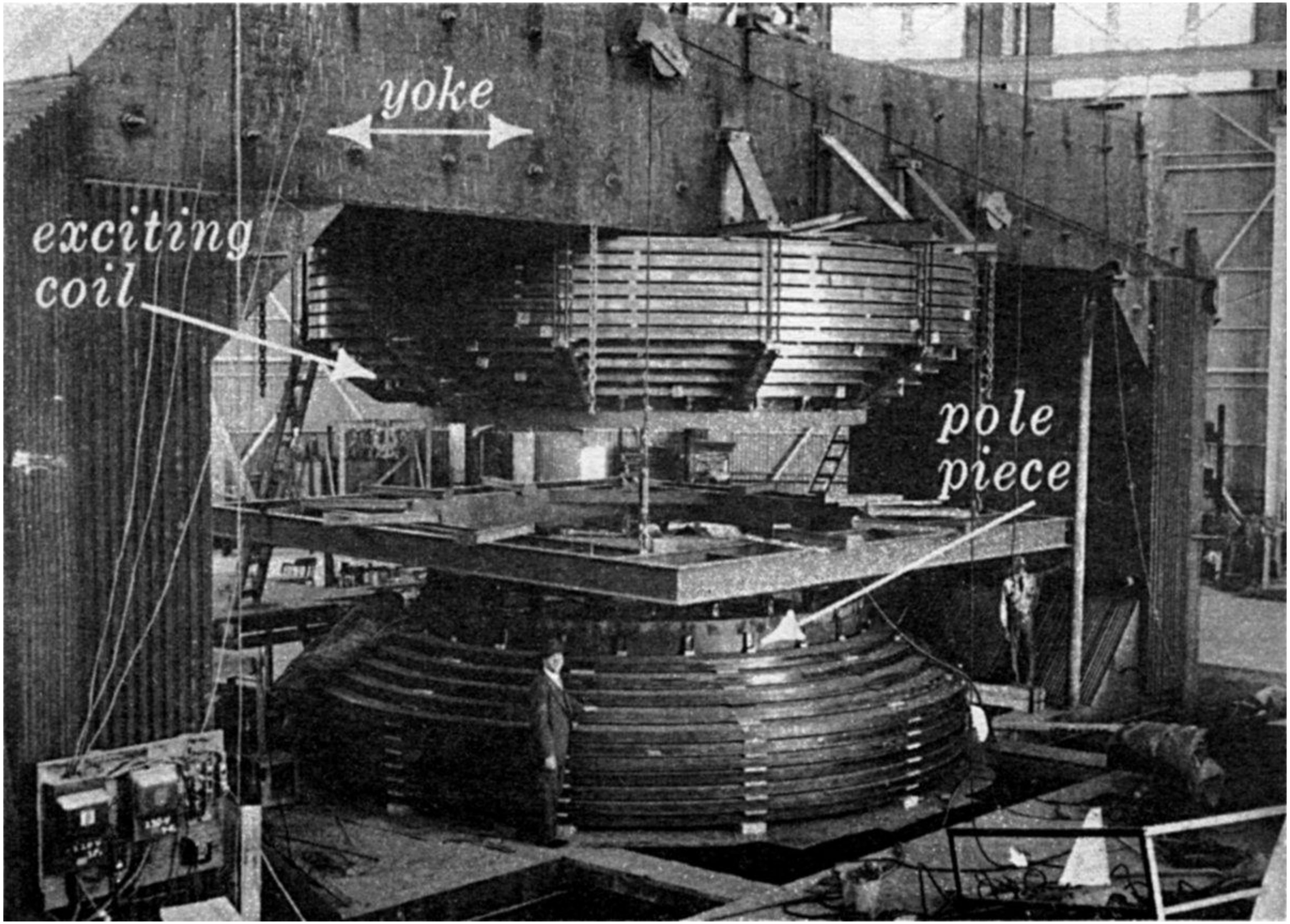
According to history, the first electromagnet (not for an accelerator) was built in England in 1824 by William Sturgeon





William Sturgeon

The working principle is the same as this large magnet, of the 184’’ (4.7 m) cyclotron at Berkeley (picture taken in 1942)



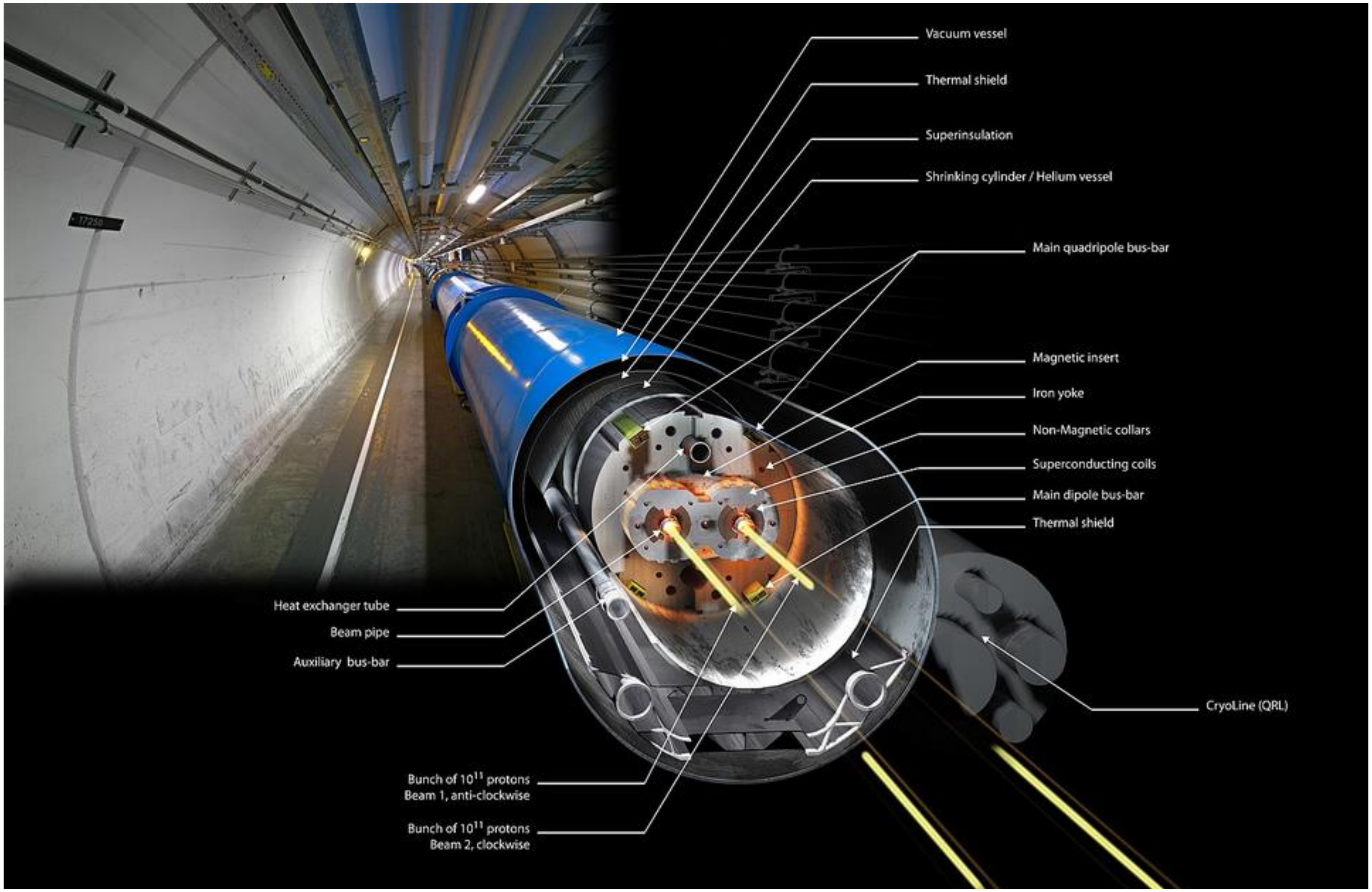
This short course is organized in several blocks

1. Introduction, jargon, general concepts and formulae
2. Resistive magnets
3. Superconducting magnets
4. Tutorial with OPERA-2D

Magnets can be classified based on their geometry / what they do to the beam

dipole	solenoid
quadrupole	combined function bending
sextupole	corrector
octupole	skew magnet
kicker	undulator / wiggler

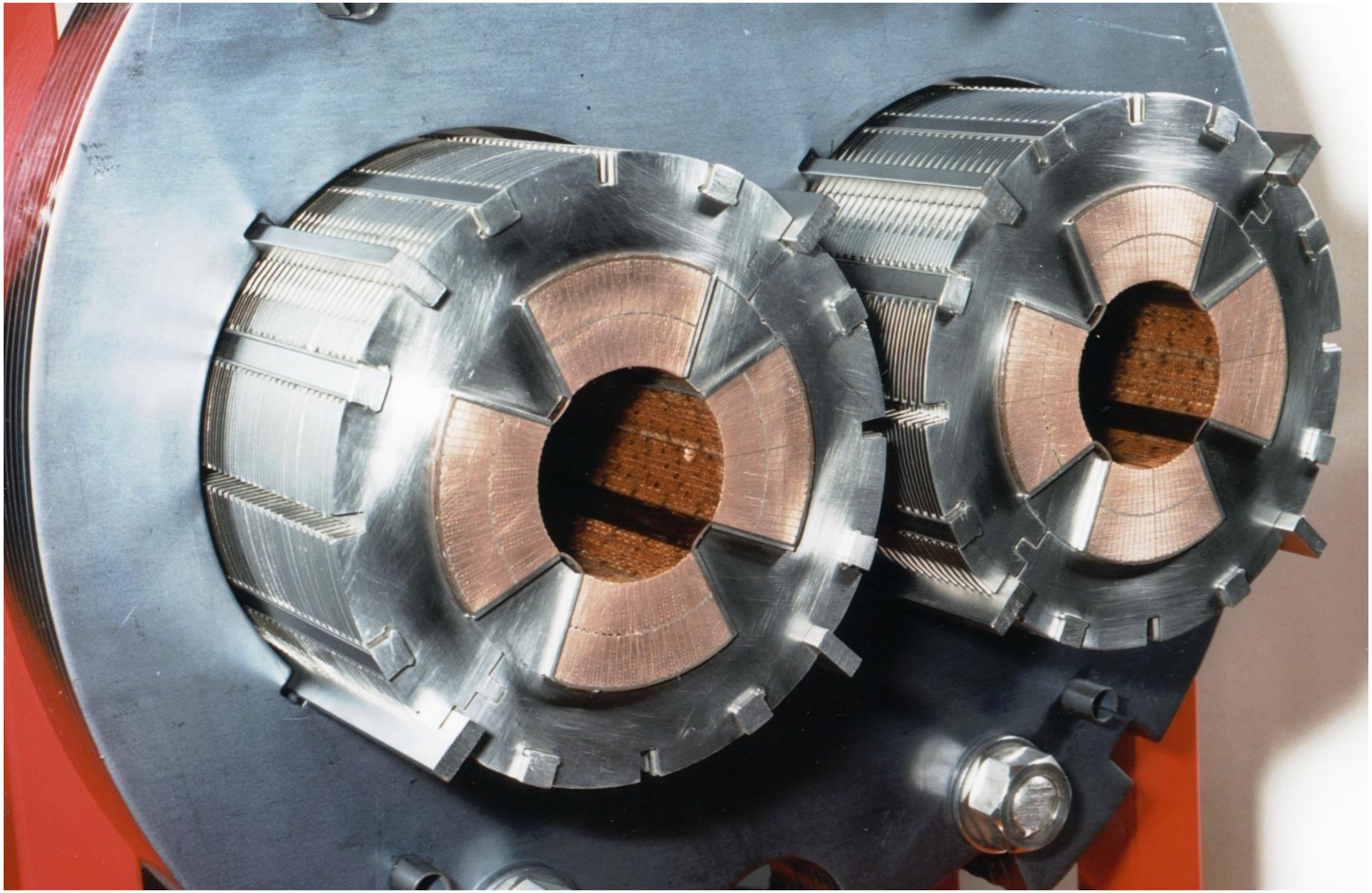
This is a main dipole of the LHC at CERN: 8.3 T × 14.3 m



These are main dipoles of the SPS at CERN: 2.0 T × 6.3 m

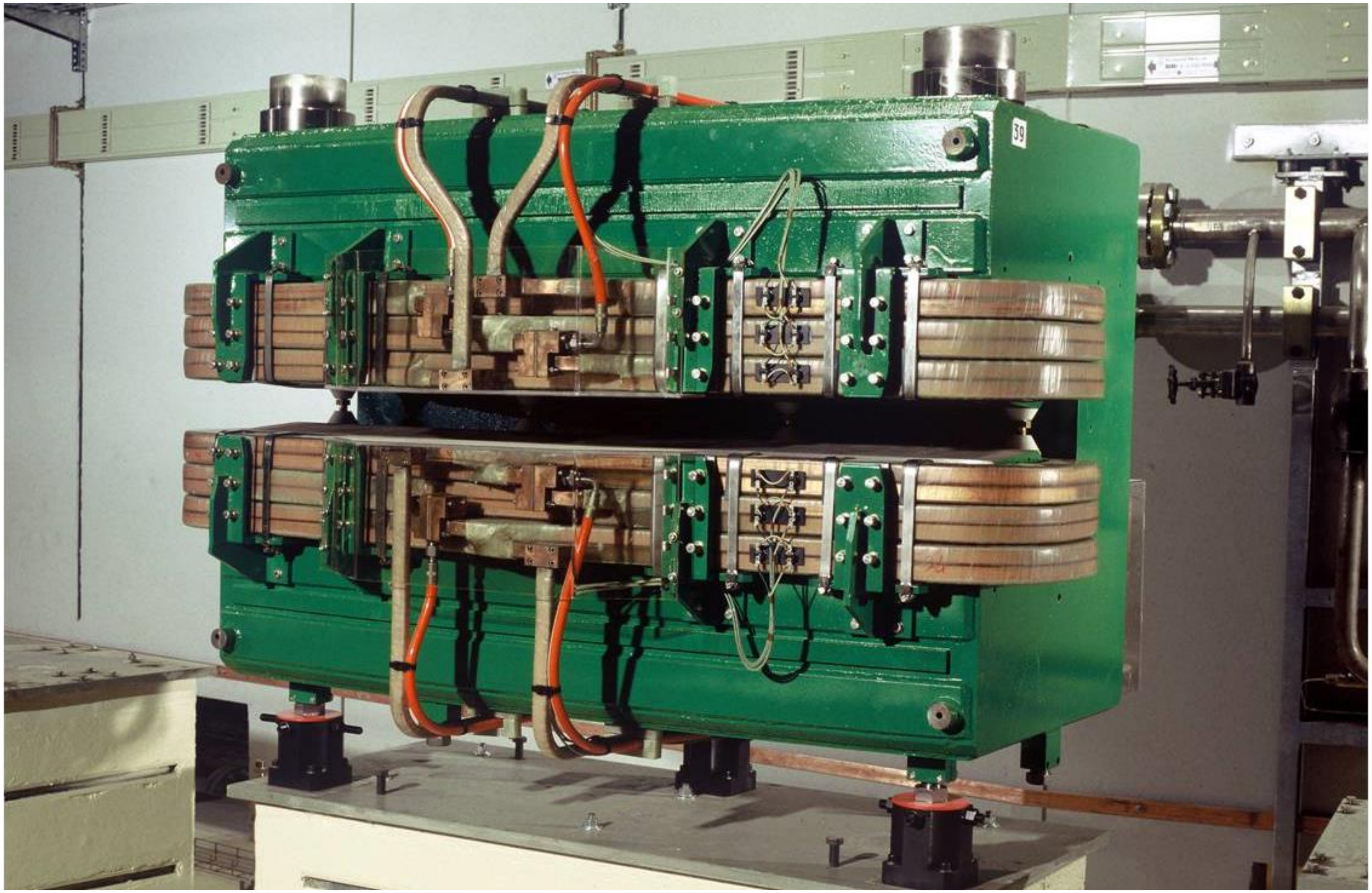
This is a cross section of a main quadrupole of the LHC at CERN:

223 T/m × 3.2 m

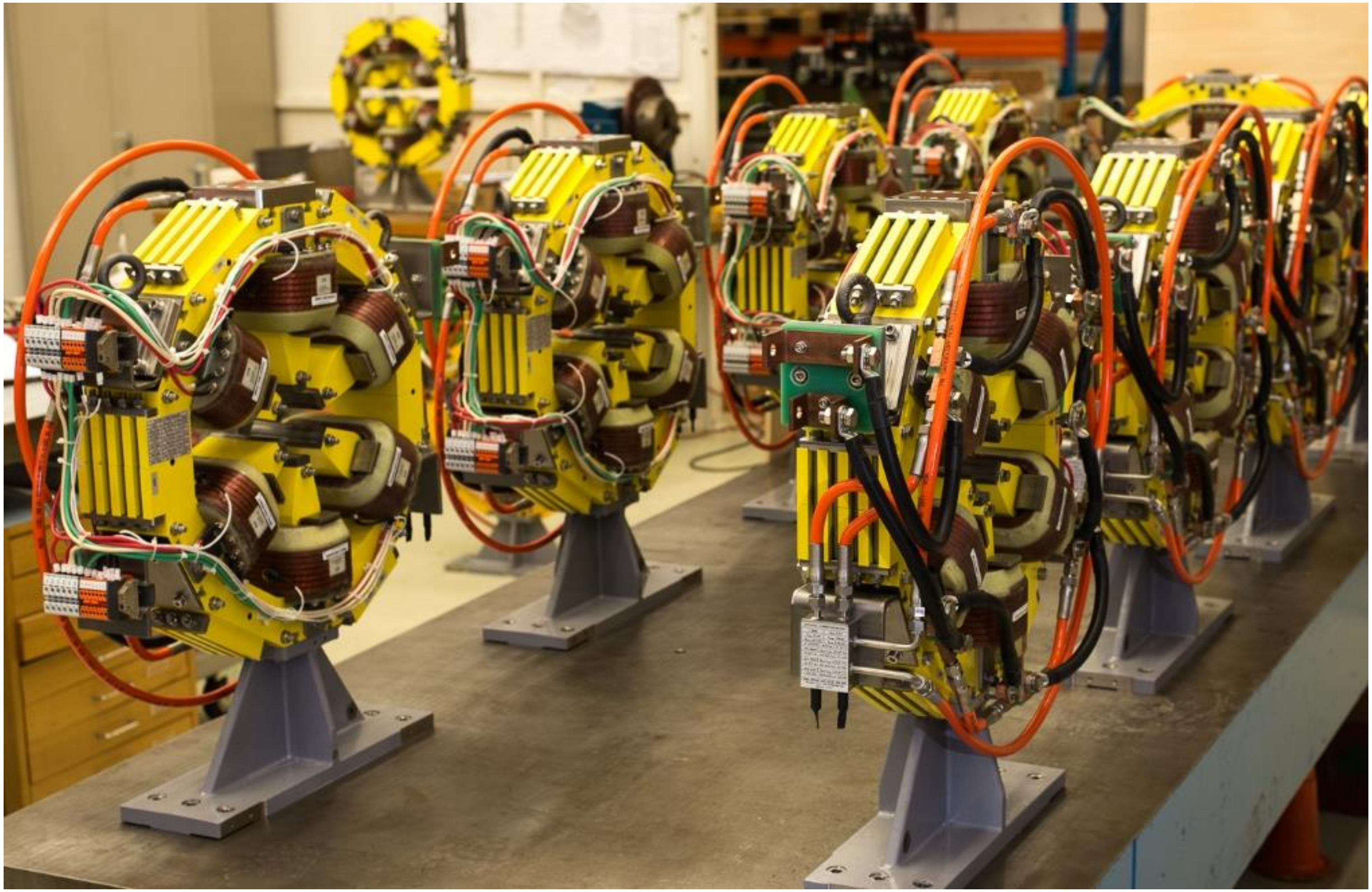


These are main quadrupoles of the SPS at CERN: 22 T/m × 3.2 m

This is a combined function bending magnet of the ELETTRA light source



These are sextupoles (with embedded correctors) of the main ring of the SESAME light source



Magnets can be classified also differently, looking for example at their technology

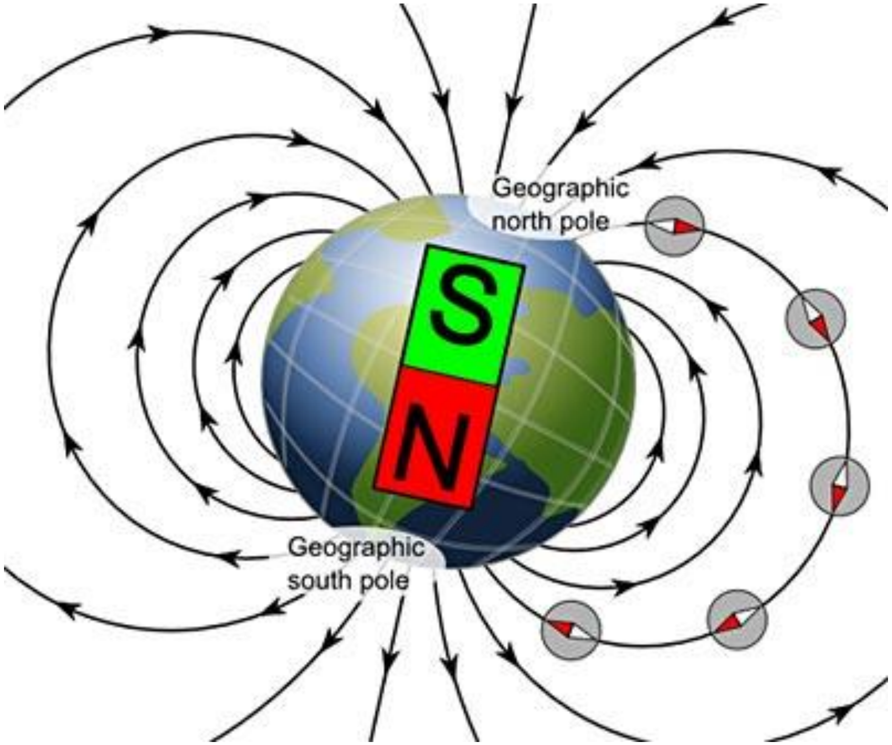
electromagnet	permanent magnet
iron dominated	coil dominated
normal conducting (resistive)	superconducting

static	cycled / ramped slow pulsed	fast pulsed

Nomenclature

B	magnetic field B field magnetic flux density magnetic induction	T (Tesla)
H	H field magnetic field strength magnetic field	A/m (Ampere/m)
μ_0	vacuum permeability	$4\pi \cdot 10^{-7}$ H/m (Henry/m)
μ_r	relative permeability	dimensionless
μ	permeability, $\mu = \mu_0 \mu_r$	H/m

The polarity comes from the direction of the flux lines, that go from a North to a South pole



in Oxford, on 25/01/2017

$|B|$ = 48728 nT = 0.048728 mT = 0.000048728 T

Magnetostatic fields are described by Maxwell's equations, coupled with a law describing the material

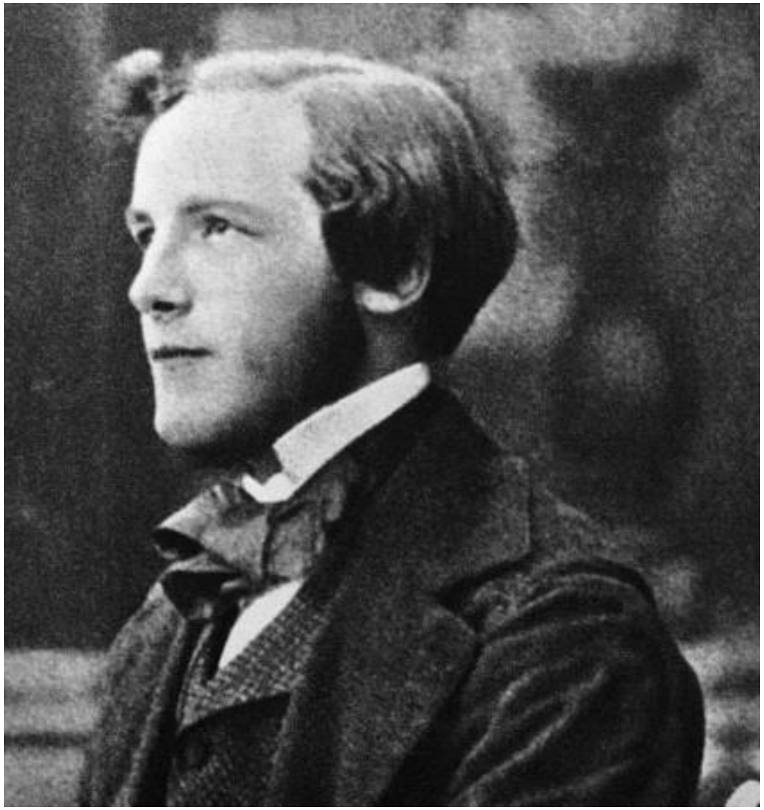
$$\mathrm{div}\,\vec{B} = 0$$

$$\oint_S \vec{B} \cdot \overrightarrow{dS} = 0$$

$$\mathrm{rot}\,\vec{H} = \vec{J}$$

$$\oint_C \vec{H} \cdot \overrightarrow{dl} = \int_S \vec{j} \cdot \overrightarrow{dS} = NI$$

$$\vec{B} = \mu_0 \mu_r \vec{H}$$



James Clerk Maxwell

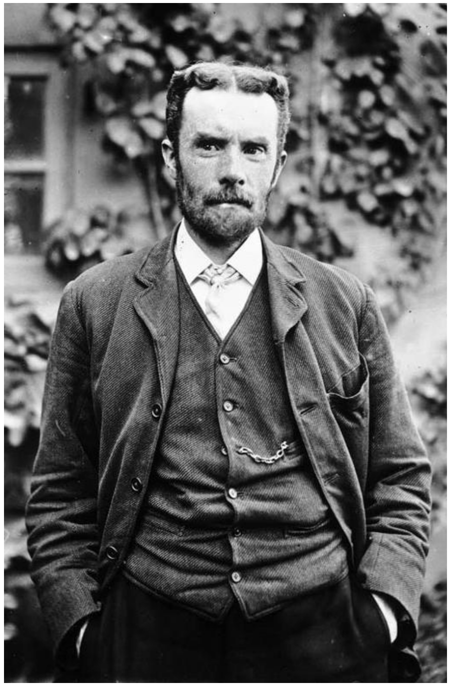
The Lorentz force is the main link between electromagnetism and mechanics

$$\vec{F} = q[\vec{E} + (\vec{v} \times \vec{B})]$$

for charged beams

$$\vec{F} = I\vec{\ell} \times \vec{B}$$

for conductors



Oliver Heaviside

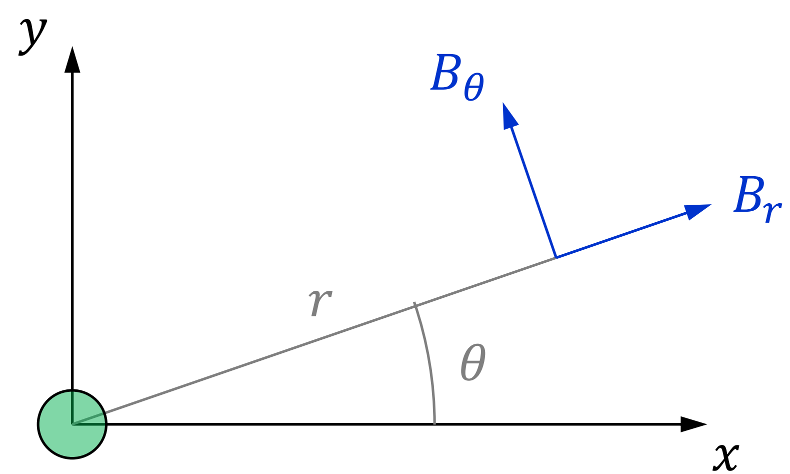
Hendrik Lorentz

Pierre-Simon, marquis de Laplace

In synchrotrons / transfer lines magnets, the B field seen from the beam is often expressed as a series of multipoles

$$B_r = \sum_{n=1}^{\infty} \left(\frac{r}{R}\right)^{n-1} [B_n \sin(n\theta) + A_n \cos(n\theta)]$$

$$B_\theta = \sum_{n=1}^{\infty} \left(\frac{r}{R}\right)^{n-1} [B_n \cos(n\theta) - A_n \sin(n\theta)]$$



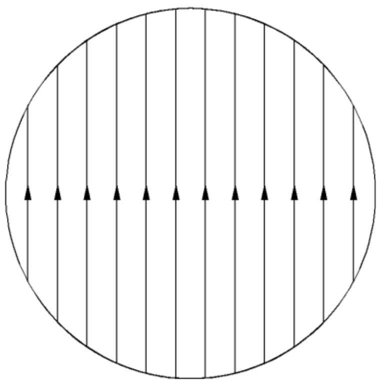
direction of the beam (orthogonal to plane)

$$B_y(z) + iB_x(z) = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{z}{R}\right)^{n-1}$$

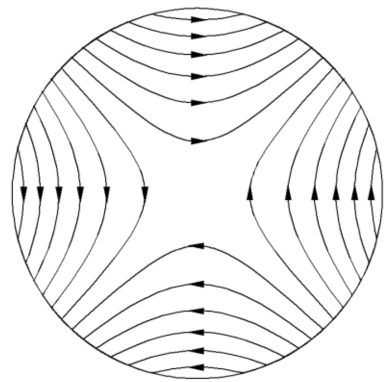
$$z = x + iy = re^{i\theta}$$

Each multipole term corresponds to a field distribution; they can be added up (exploiting linear superposition)

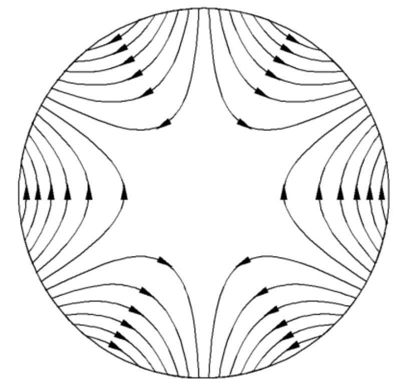
B_1: normal dipole



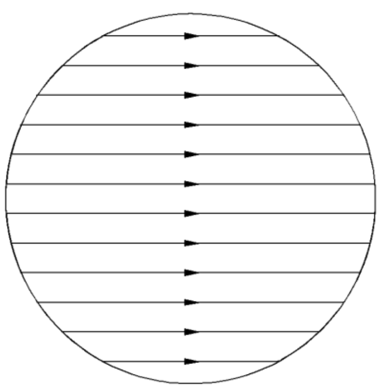
B_2: normal quadrupole



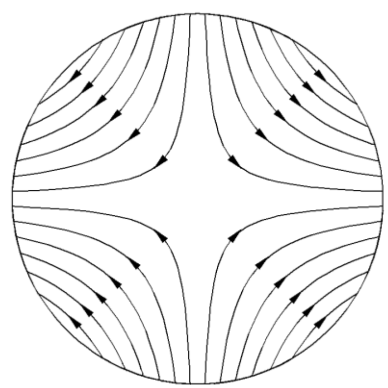
B_3: normal sextupole



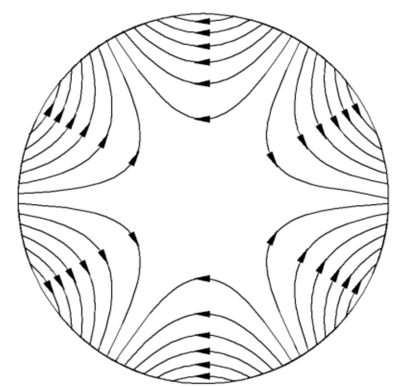
A_1: skew dipole



A_2: skew quadrupole

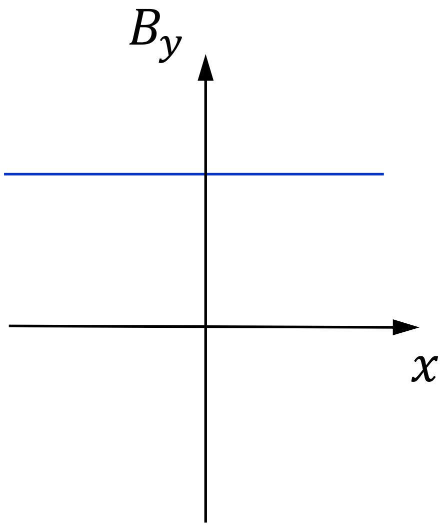


A_3: skew sextupole

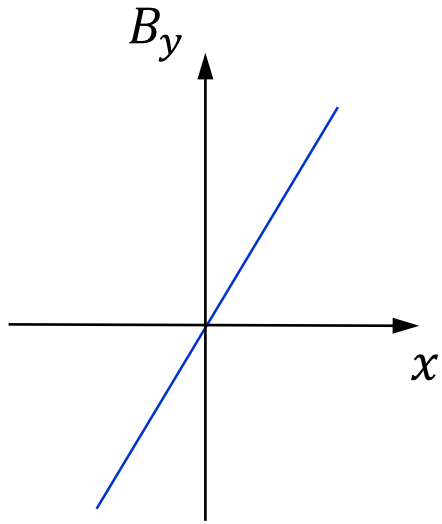


The field profile in the horizontal plane follows a polynomial expansion

$$B_y(x) = \sum_{n=1}^{\infty} B_n \left(\frac{x}{R}\right)^{n-1} = B_1 + B_2 \frac{x}{R} + B_3 \frac{x^2}{R^2} + \cdots$$

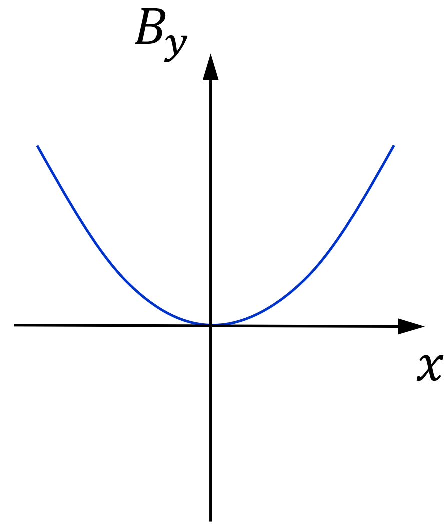


B_1: dipole



B_2: quadrupole

$$G = \frac{B_2}{R} = \frac{\partial B_y}{\partial x}$$



B_3: sextupole

$$B'' = \frac{2B_3}{R^2}$$

For optics calculation, usually the field or multipole component is given, together with the (magnetic) length: ex. from MAD-X

Dipole

bend angle α [rad] & length L [m]

k_0 [1/m] & length L [m] obsolete

$k_0 = B / (B\rho)$ $B = B_1$

Quadrupole

quadrupole coefficient k_1 [1/m^2] × length L [m]

$k_1 = (dB_y/dx) / (B\rho)$

$G = dB_y/dx = B_2/R$

Sextupole

sextupole coefficient k_2 [1/m^3] × length L [m]

$k_2 = (d^2B_y/dx^2) / (B\rho)$

$(d^2B_y/dx^2)/2! = B_3/R^2$

Here is how to compute magnetic quantities from MAD-X entries, and vice versa

```
BEAM, PARTICLE=ELECTRON,PC=3.0;
DEGREE:=PI/180.0;
QF: QUADRUPOLE,L=0.5,K1=0.2;
QD: QUADRUPOLE,L=1.0,K1=-0.2;
B: SBEND,L=1.0,ANGLE=15.0*DEGREE;
```

$(B\rho) = 10^9/c*PC$ = 10^9/299792485*3.0 = 10.01 Tm

<u>dipole</u> (SBEND)

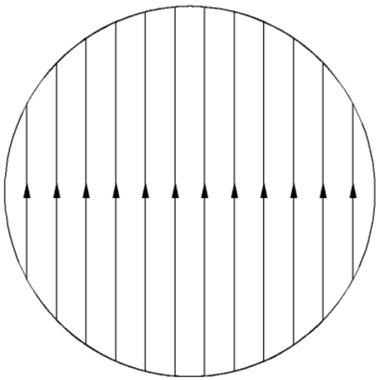
B = |ANGLE|/L*(Bρ) = (15*pi/180)/1.0*10.01 = 2.62 T

<u>quadrupole</u>

G = |K1|*(Bρ) = 0.2*10.01 = 2.00 T/m

The harmonic decomposition is used also to describe the field quality (or field homogeneity), that is, the deviations of the actual B with respect to the ideal one

(normal) dipole



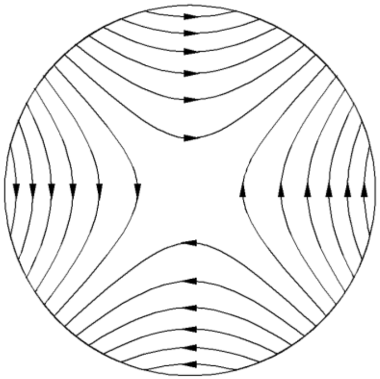
$$\vec{B}_{id}(x,y) = B_1\vec{J}$$

$$B_y(z) + iB_x(z) =$$
$$= B_1 + \frac{B_1}{10000}\left[ia_1 + (b_2 + ia_2)\left(\frac{z}{R}\right) + (b_3 + ia_3)\left(\frac{z}{R}\right)^2 + (b_4 + ia_4)\left(\frac{z}{R}\right)^3 + \cdots\right]$$

$$b_2 = 10000\frac{B_2}{B_1} \quad b_3 = 10000\frac{B_3}{B_1} \quad a_1 = 10000\frac{A_1}{B_1} \quad a_2 = 10000\frac{A_2}{B_1} \quad \ldots$$

The same expression can be written for a quadrupole

(normal) quadrupole

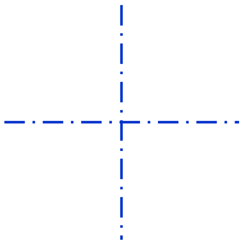


$$\vec{B}_{id}(x,y) = B_2[x\vec{j} + y\vec{i}]\frac{1}{R}$$

$$B_y(z) + iB_x(z) =$$
$$= B_2\frac{z}{R} + \frac{B_2}{10000}\left[ia_2\left(\frac{z}{R}\right) + (b_3 + ia_3)\left(\frac{z}{R}\right)^2 + (b_4 + ia_4)\left(\frac{z}{R}\right)^3 + \cdots\right]$$

$$b_3 = 10000\frac{B_3}{B_2} \quad b_4 = 10000\frac{B_4}{B_2} \quad a_2 = 10000\frac{A_2}{B_2} \quad \ldots$$

The *allowed* / *not-allowed* harmonics refer to some terms that shall / shall not cancel out thanks to design symmetries



fully symmetric dipoles

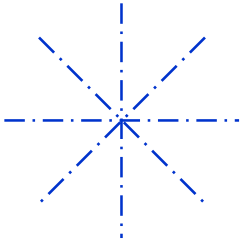
allowed: B_1, b_3, b_5, b_7, b_9, etc.

not-allowed: all the others

half symmetric dipoles

allowed: B_1, b_2, b_3, b_4, b_5, etc.

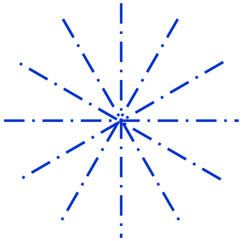
not-allowed: all the others



fully symmetric quadrupoles

allowed: B_2, b_6, b_{10}, b_{14}, b_{18}, etc.

not-allowed: all the others



fully symmetric sextupoles

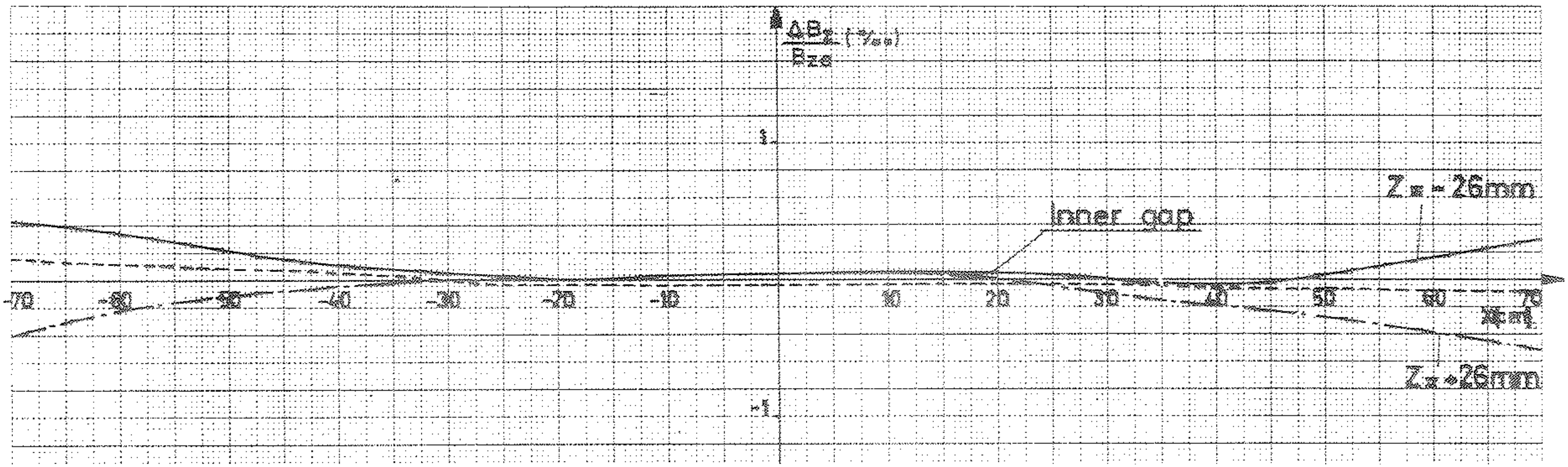
allowed: B_3, b_9, b_{15}, b_{21}, etc.

not-allowed: all the others

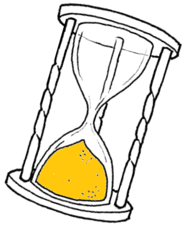
The field quality is often also shown with a ΔB/B plot

$$\frac{\Delta B}{B} = \frac{B(x,y) - B_{id}(x,y)}{B_{id}(x,y)}$$

done on one component, usually B_y for a dipole



ΔB/B can (at least locally) be expressed from the harmonics: this is the expansion for a dipole



$$B_{y,id}(x) = B_1$$

$$B_y(x) = B_1 + \frac{B_1}{10000}\left[b_2\left(\frac{x}{R}\right) + b_3\left(\frac{x}{R}\right)^2 + b_4\left(\frac{x}{R}\right)^3 + \cdots\right]$$

$$\frac{\Delta B}{B}(x) = \frac{1}{10000}\left[b_2\left(\frac{x}{R}\right) + b_3\left(\frac{x}{R}\right)^2 + b_4\left(\frac{x}{R}\right)^3 + \cdots\right]$$

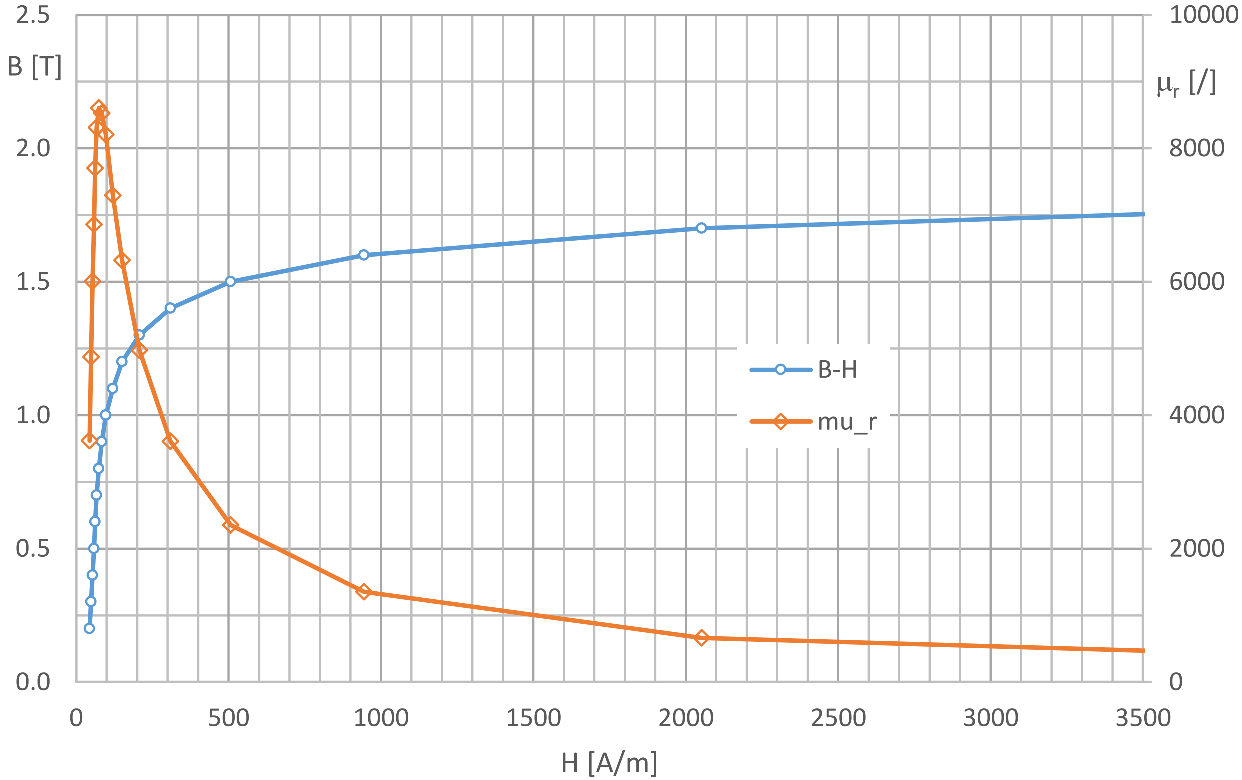
1. Introduction, jargon, general concepts and formulae

2. Resistive magnets

3. Superconducting magnets

4. Tutorial with OPERA-2D

Resistive magnets are in most cases “iron-dominated”: the BH response of the yoke material is important



curves for typical M1200-100 A electrical steel

These are typical fields for resistive dipoles and quadrupoles, taken from machines at CERN

PS @ 26 GeV

combined function bending $B = 1.5$ T

SPS @ 450 GeV

bending $B = 2.0$ T

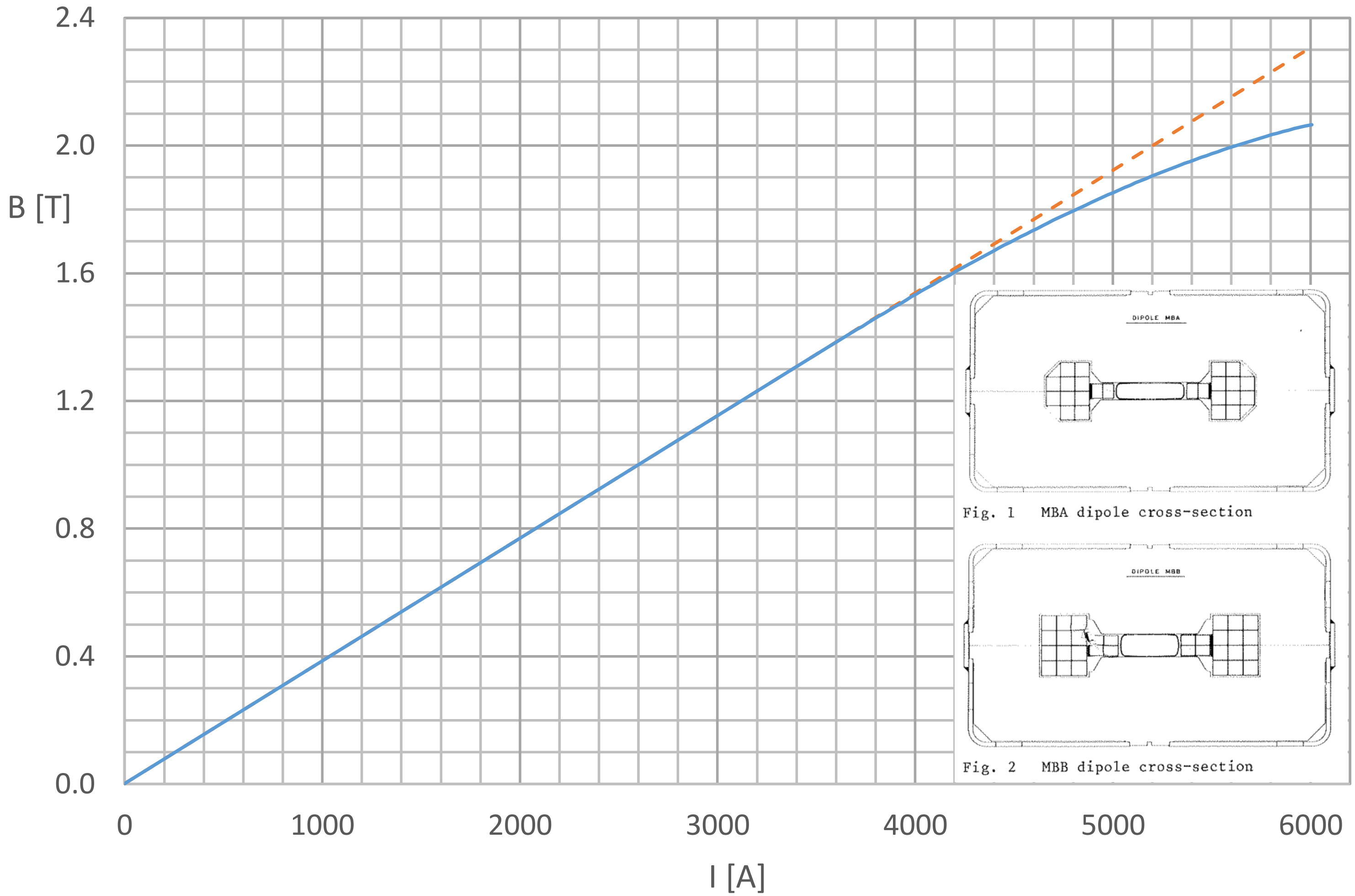
quadrupole $B_{pole} = 21.7*0.044 = 0.95$ T

TI2 / TI8 (transfer lines SPS to LHC, @ 450 GeV)

bending $B = 1.8$ T

quadrupole $B_{pole} = 53.5*0.016 = 0.86$ T

This is the (average) transfer function field B vs. current I for the SPS main dipoles



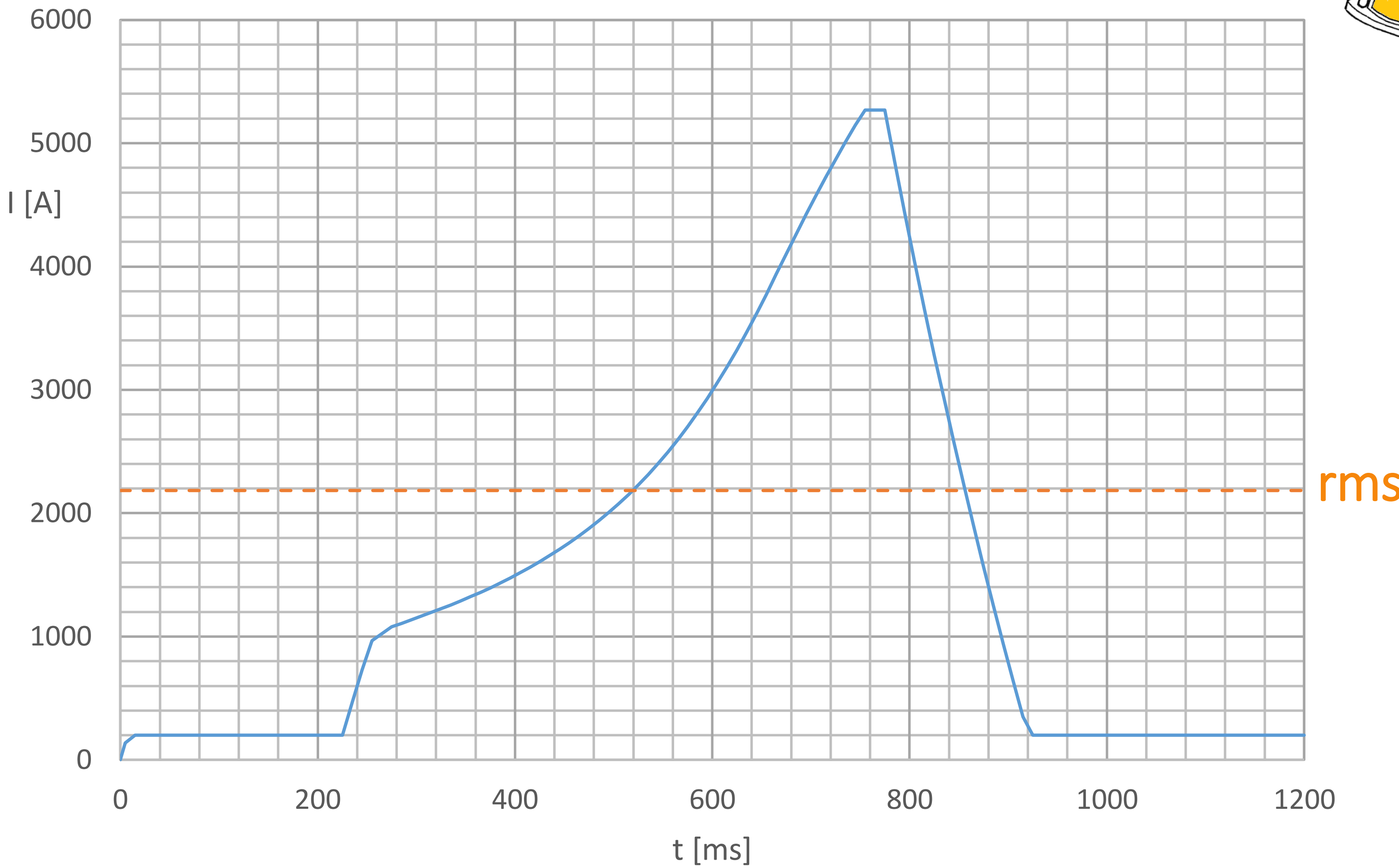
If the magnet is not dc, then an rms power / current is taken, considering the duty cycle

$$P_{rms} = RI_{rms}^2 = \frac{1}{T}\int_0^T R[I(t)]^2 dt$$

for a pure sine wave $$I_{rms} = \frac{I_{peak}}{\sqrt{2}}$$

for a linear ramp from 0 $$I_{rms} = \frac{I_{peak}}{\sqrt{3}}$$

This will be a cycle to 2.0 GeV of the PSB at CERN after the upgrade planned from 2019-2020



For resistive coils, the material is most often copper, sometimes aluminum

	Cu	Al
raw metal price	≈ 6500 $/ton	≈ 1800 $/ton
electrical resistivity	$1.72 \cdot 10^{-8}\ \Omega/\text{m}$	$2.65 \cdot 10^{-8}\ \Omega/\text{m}$
density	$8.9\ \text{kg/dm}^3$	$2.7\ \text{kg/dm}^3$

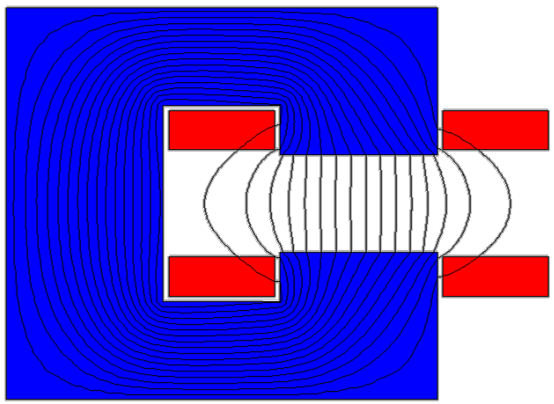
LHCb detector dipole

Al coils

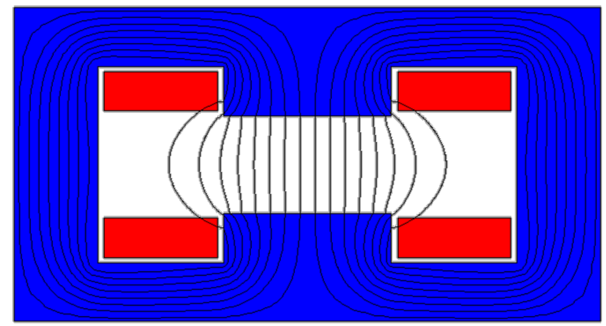
coil mass 2 × 25 t

power 2 × 2.1 MW

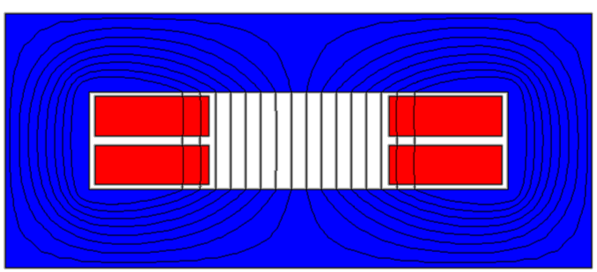
These are the most common types of resistive dipoles



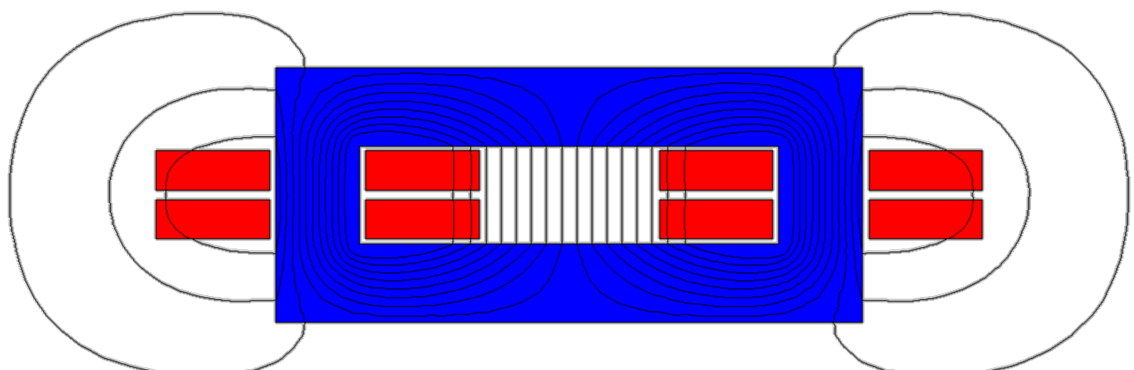
“C”



“H”

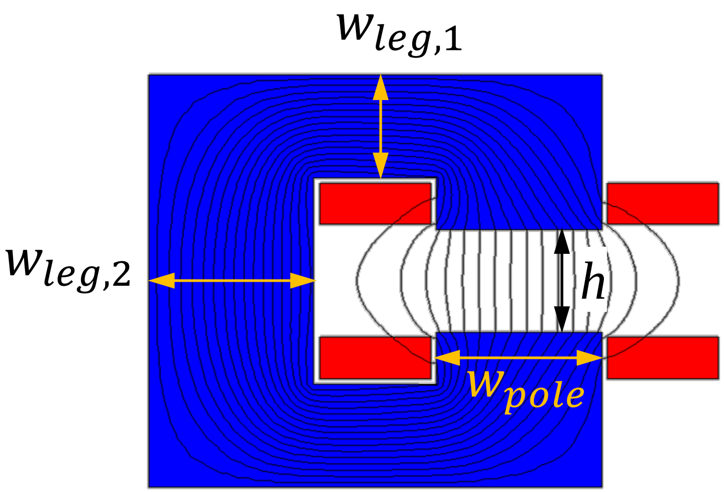


window frame
(“O”)



window frame (“O”)
with windings on both backlegs

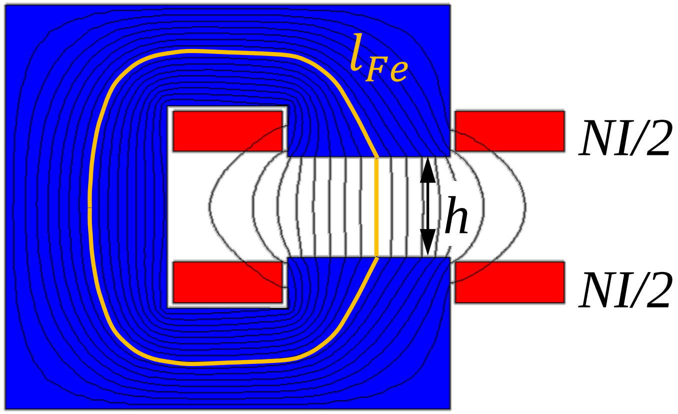
The magnetic circuit is dimensioned so that the pole is wide enough for field quality, and there is enough room for the flux in the return legs



$$w_{pole} \cong w_{GFR} + 2.5h$$

$$B_{leg} \cong B_{gap} \frac{w_{pole} + 1.2h}{w_{leg}}$$

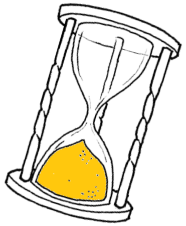
The Ampere-turns are a linear function of the gap and of the B field (at least up to saturation)



$$NI = \oint \vec{H} \cdot \vec{dl} = \frac{B_{Fe}}{\mu_0 \mu_r} \cdot l_{Fe} + \frac{B_{gap}}{\mu_0} \cdot h \cong \frac{B_{gap} h}{\mu_0}$$

$$NI = \frac{Bh}{\eta \mu_0} \qquad \eta = \frac{1}{1 + \frac{1}{\mu_r} \frac{l_{Fe}}{h}}$$

The same can be solved using magnetic reluctances and Hopkinson’s law, which is a parallel of Ohm’s law



$$\mathcal{R} = \frac{\mathrm{NI}}{\Phi}$$

$$\mathrm{R} = \frac{\mathrm{V}}{I}$$

$$\mathcal{R} = \frac{l}{\mu_0 \mu_r A}$$

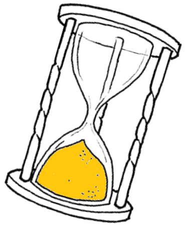
$$\mathrm{R} = \frac{l}{\sigma S}$$

$$\eta = \frac{1}{1 + \frac{\mathcal{R}_{Fe}}{\mathcal{R}_{gap}}}$$

Example of computation of Ampere-turns and current

central field B = 1.5 T
total gap 80 mm

$$NI = \frac{Bh}{\eta\mu_0}$$



$\eta \cong 0.97$

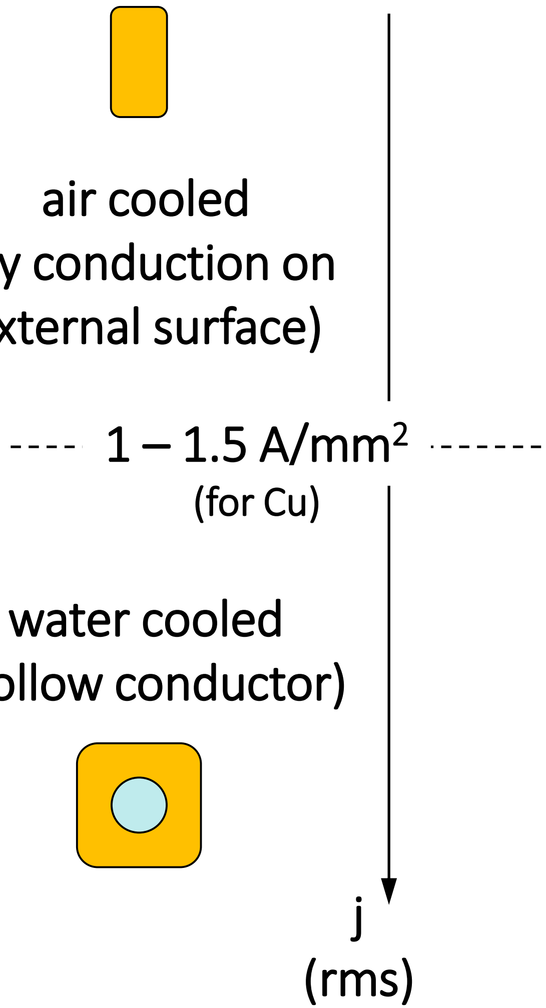
NI = (1.5*0.080)/(0.97*4*pi*10^-7) = 98446 A total

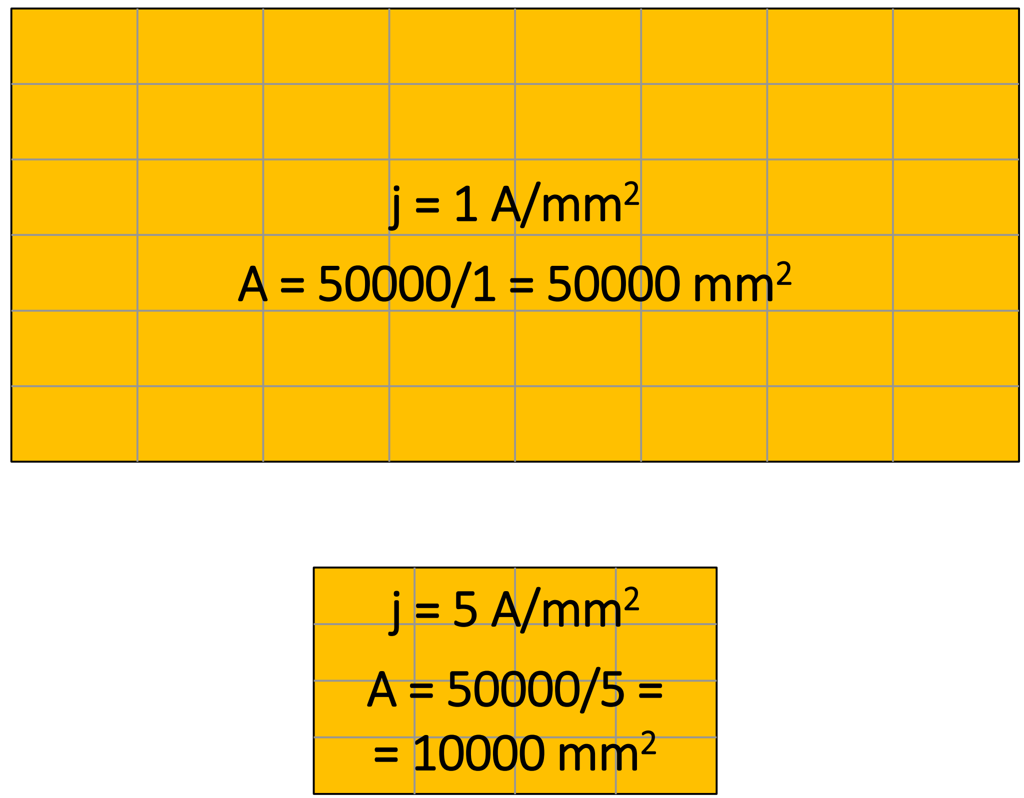
<u>low inductance option</u>
64 turns, I ≅ 98500/64 = 1540 A
L = 62.9 mH, R = 15.0 mΩ

<u>low current option</u>
204 turns, I ≅ 98500/204 = 483 A
L = 639 mH, R = 160 mΩ

Besides the number of turns, the overall size of the coil depends on the current density j, which drives the resistive power consumption (linearly)

ex. NI = 50000 A (rms)





These are common formulae for the main electric parameters of a resistive dipole (1/2)

Ampere-turns (total) $$NI = \frac{Bh}{\eta\mu_0}$$

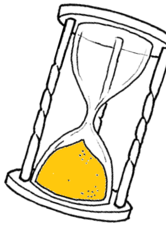
current $$I = \frac{(NI)}{N}$$

resistance (total) $$R = \frac{\rho N L_{turn}}{A_{cond}}$$

inductance $$L \cong \eta\mu_0 N^2 A/h$$

$$A \cong (w_{pole}+1.2h)(l_{Fe}+h)$$

These are common formulae for the main electric parameters of a resistive dipole (2/2)



voltage $$V = RI + L\frac{dI}{dt}$$

resistive power (rms) $$P_{rms} = RI_{rms}^2$$

$$= \rho j_{rms}^2 V_{cond}$$

$$= \frac{\rho L_{turn} B_{rms} h}{\eta \mu_0} j_{rms}$$

magnetic stored energy $$E_m = \frac{1}{2} L I^2$$

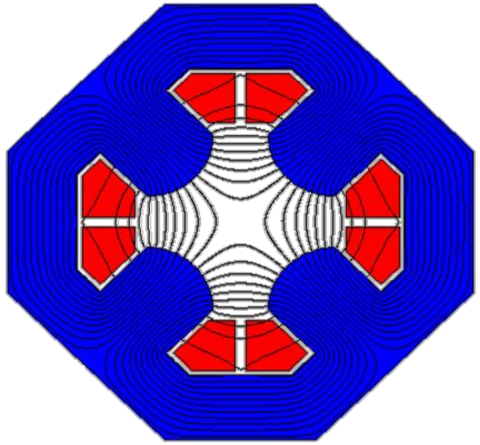
The table describes the field quality – in terms of allowed multipoles – for the different layouts of these examples

	C-shaped	H-shaped	O-shaped
b_2	1.4	0	0
b_3	-88.2	-87.0	0.2
b_4	0.7	0	0
b_5	-31.6	-31.4	-0.1
b_6	0.1	0	0
b_7	-3.8	-3.8	-0.1
b_8	0.0	0	0
b_9	0.0	0.0	0.0

b_n multipoles in units of 10^{-4} at R = 17 mm

NI = 20 kA, h = 50 mm, w_{pole} = 80 mm

These are the most common types of resistive quadrupoles



standard
quadrupole

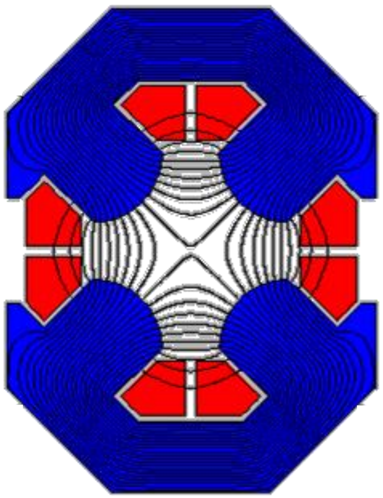
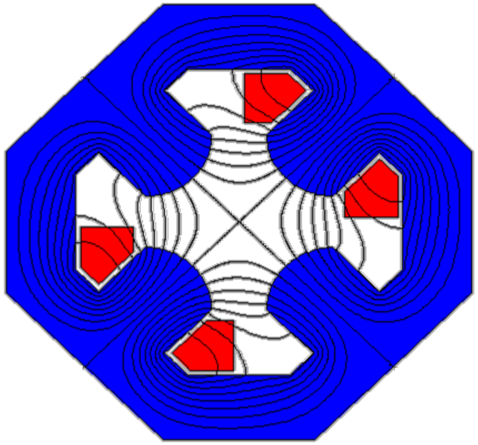


figure-of-8
(useful because narrow)



quadrupole
with half the coils
(maybe not so common)

These are useful formulae for standard resistive quadrupoles

Pole tip field	$B_{pole} = Gr$
Ampere-turns (per pole)	$NI = \frac{Gr^2}{2\eta\mu_0}$
current	$I = \frac{(NI)}{N}$
resistance (total)	$R = 4\frac{\rho N L_{turn}}{A_{cond}}$

These are useful formulae for the main cooling parameters of a water cooled resistive magnet

cooling flow $$Q_{tot} \cong 14.3 \frac{P}{\Delta T} \qquad Q_{tot} \cong N_{hydr} Q$$

water velocity $$v = \frac{1000}{15\pi d^2} Q$$

Reynolds number $$Re \cong 1400 dv$$

pressure drop $$\Delta p = 60 L_{hydr} \frac{Q^{1.75}}{d^{4.75}}$$

The *ideal* poles for dipole, quadrupole, sextupole, etc. are lines of constant scalar potential

dipole

$\rho \sin(\theta) = \pm h/2$ $\qquad$ $y = \pm h/2$ $\qquad$ straight line

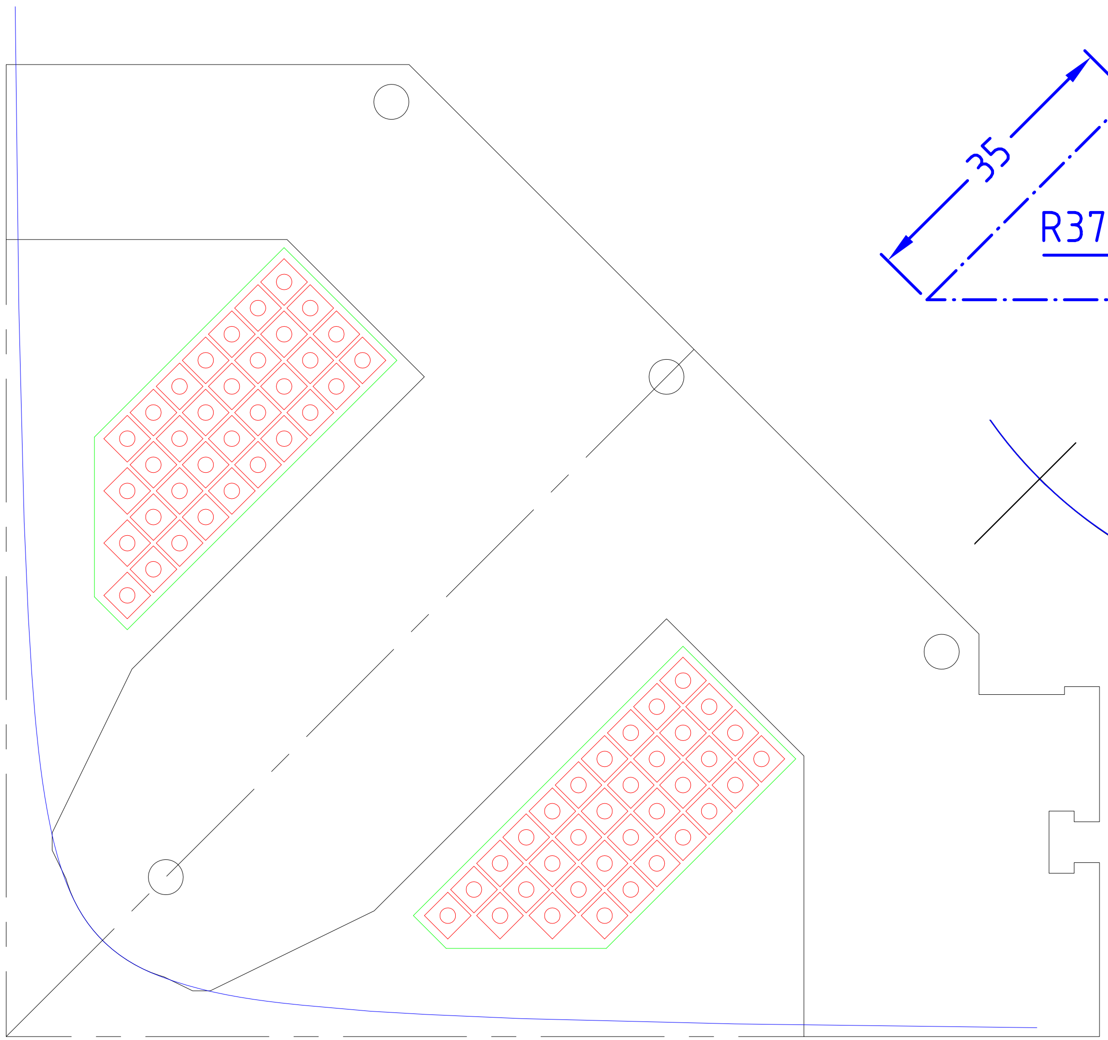
quadrupole

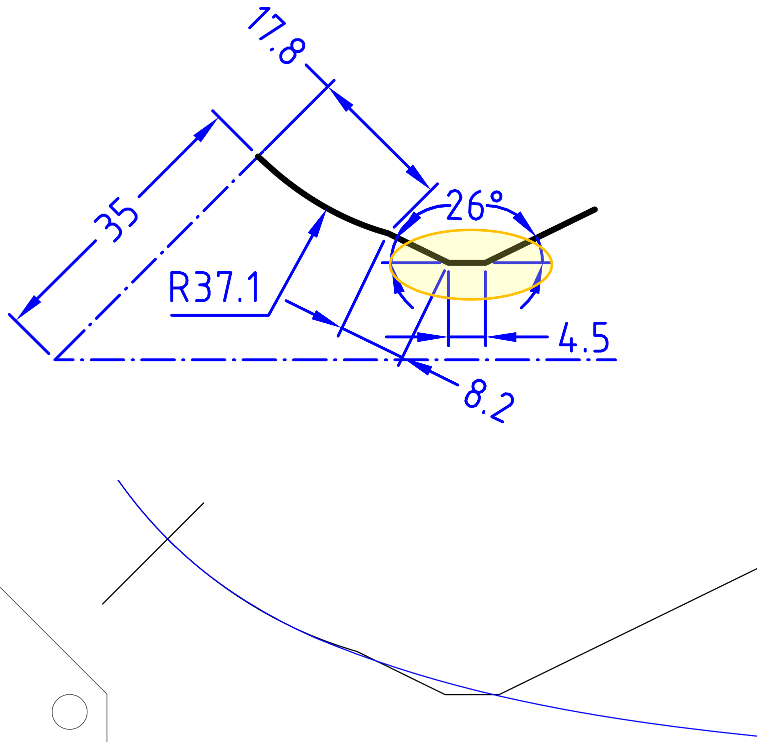
$\rho^2 \sin(2\theta) = \pm r^2$ $\qquad$ $2xy = \pm r^2$ $\qquad$ hyperbola

sextupole

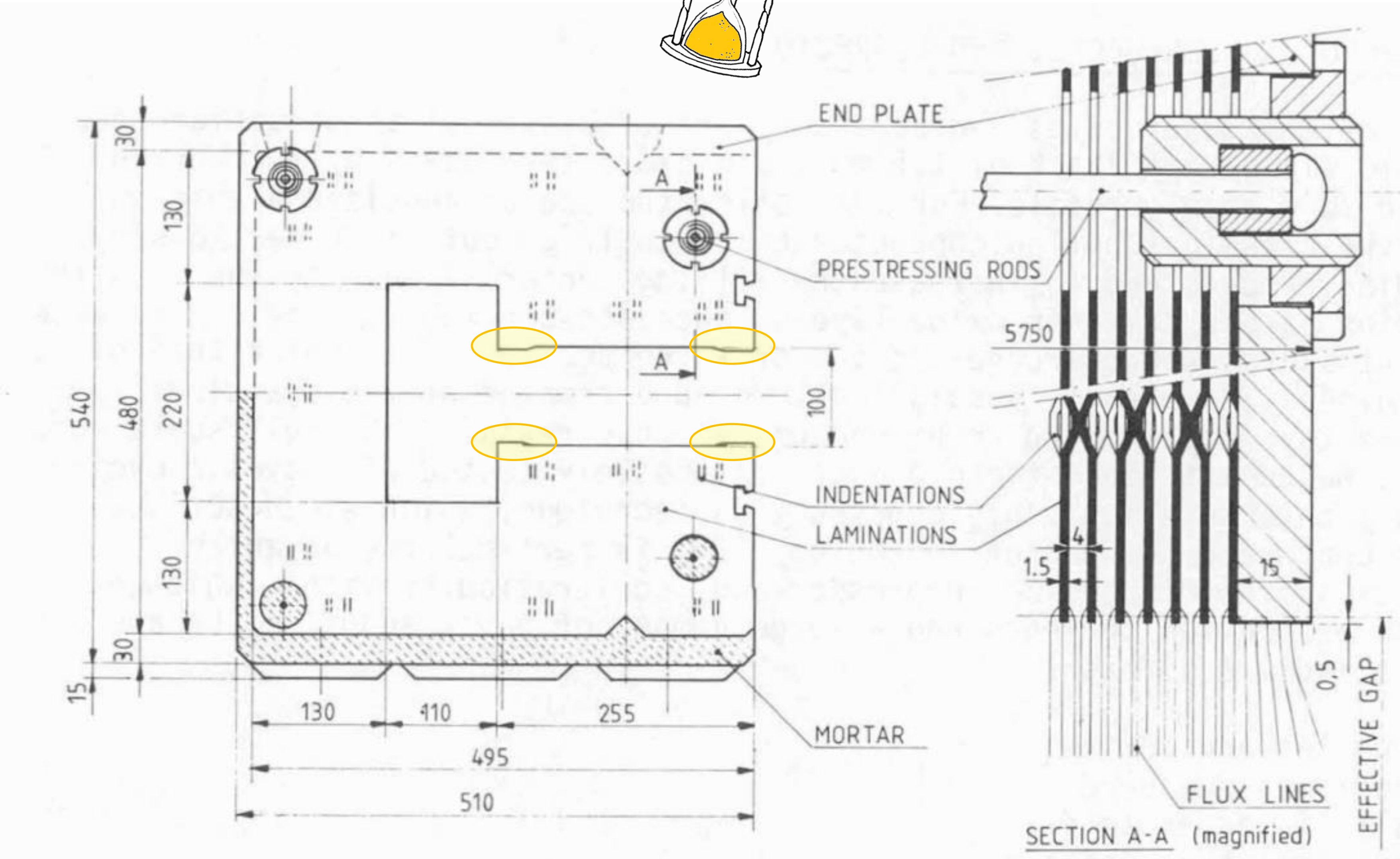
$\rho^3 \sin(3\theta) = \pm r^3$ $\qquad$ $3x^2 y - y^3 = \pm r^3$

As an example, this is the pole tip used in the SESAME quadrupoles vs. the theoretical hyperbola

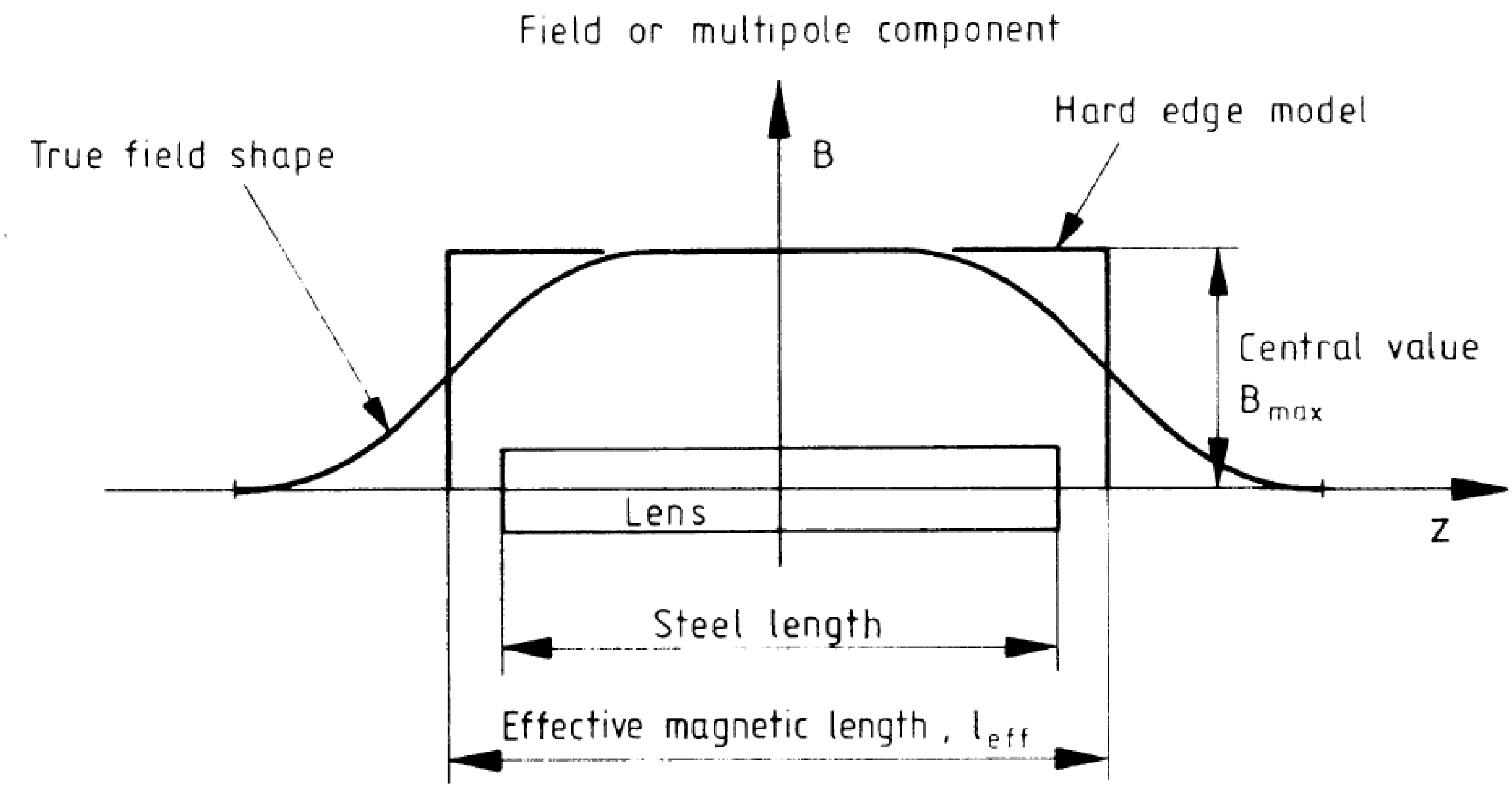




This is the lamination of the LEP main bending magnets, with the pole shims well visible



In 3D, the longitudinal dimension of the magnet is described by a magnetic length



$$l_m B_0 = \int_{-\infty}^{\infty} B(z)dz$$

The magnetic length can be estimated at first order with simple formulae

$$l_m > l_{Fe}$$

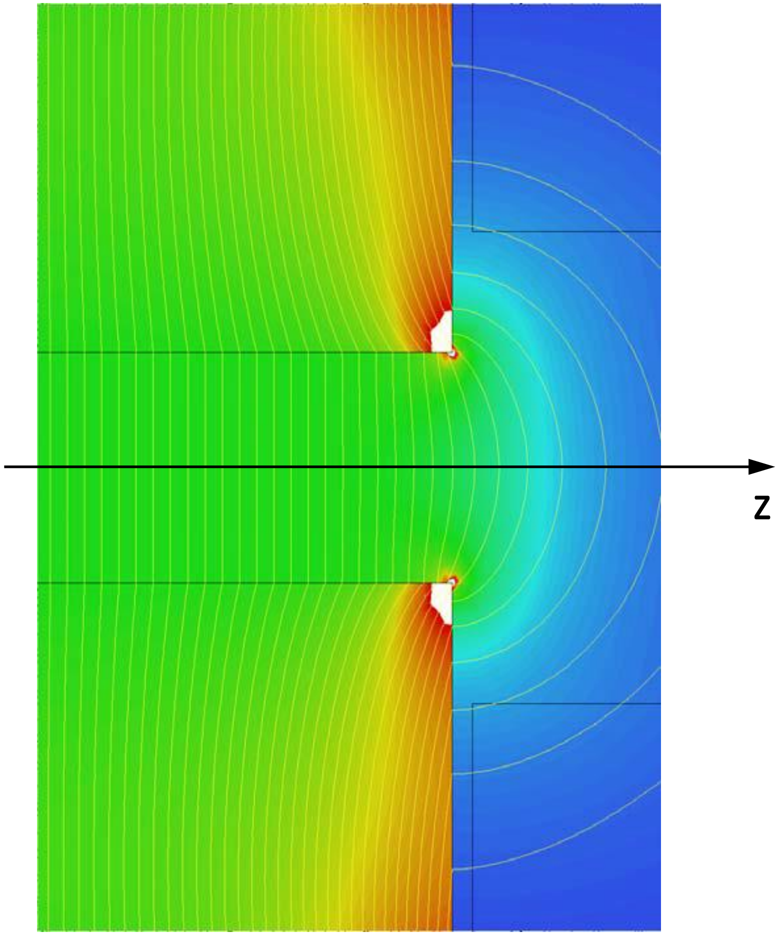
dipole

$$l_m \cong l_{Fe} + h$$

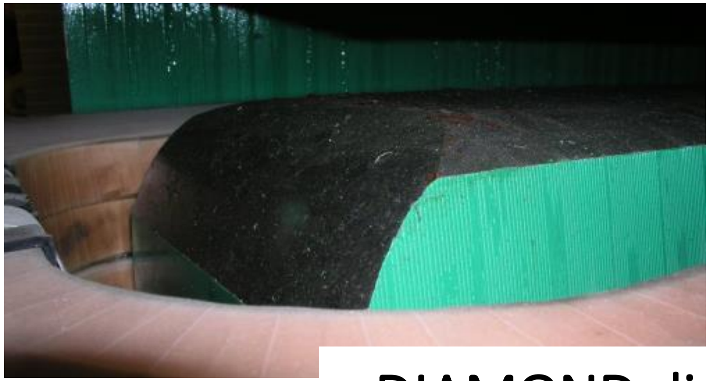
quadrupole

$$l_m \cong l_{Fe} + 0.80r$$

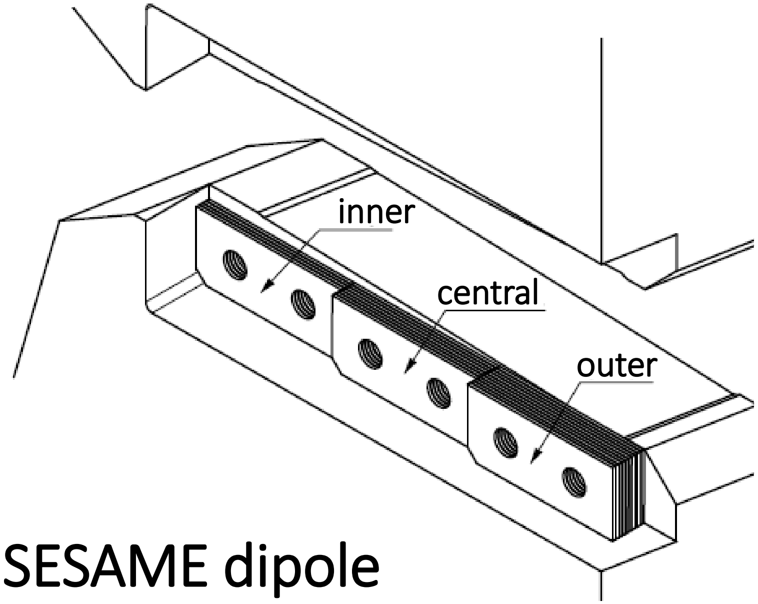
There are many different options to terminate the pole ends, depending on the type of magnet, its field level, etc.



abrupt

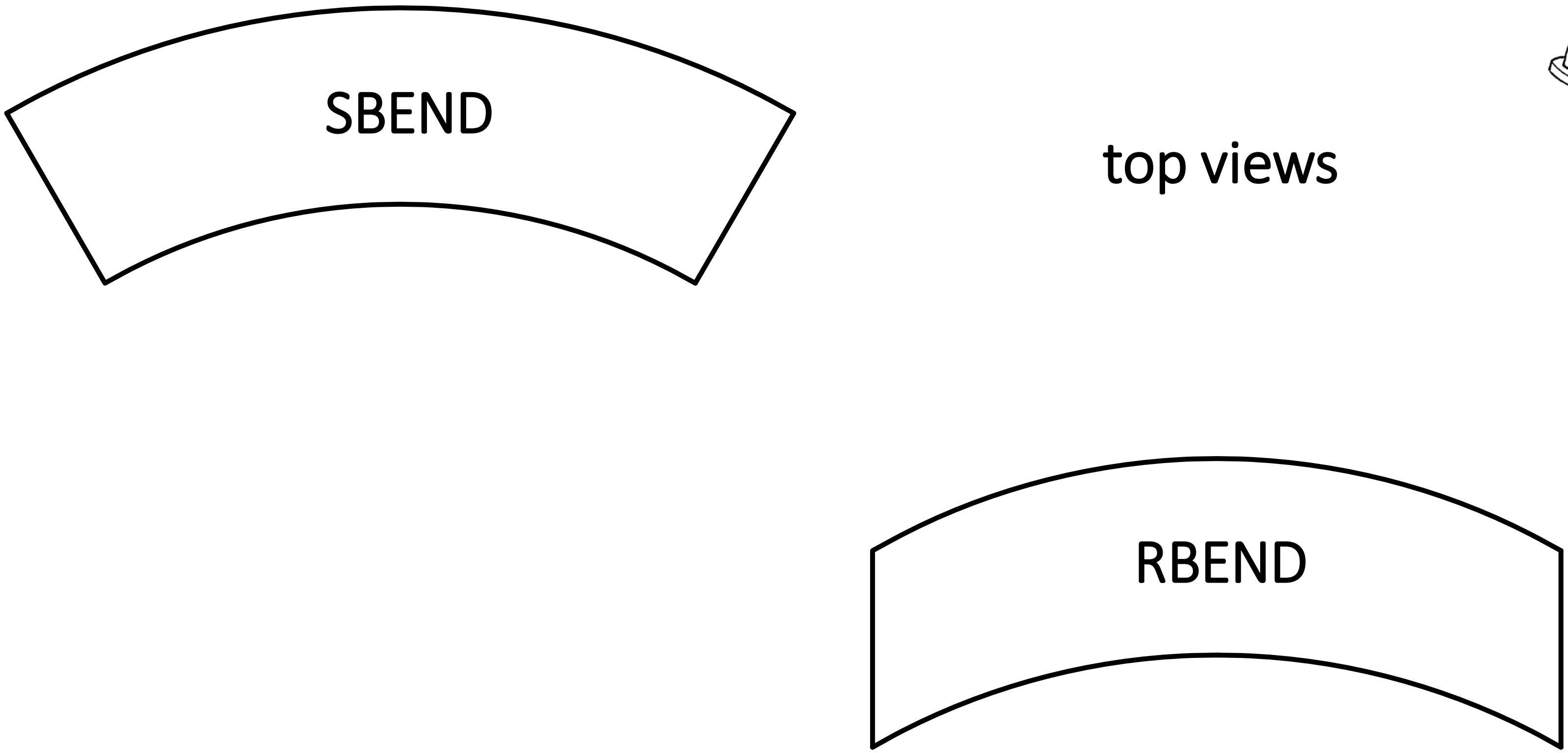


DIAMOND dipole

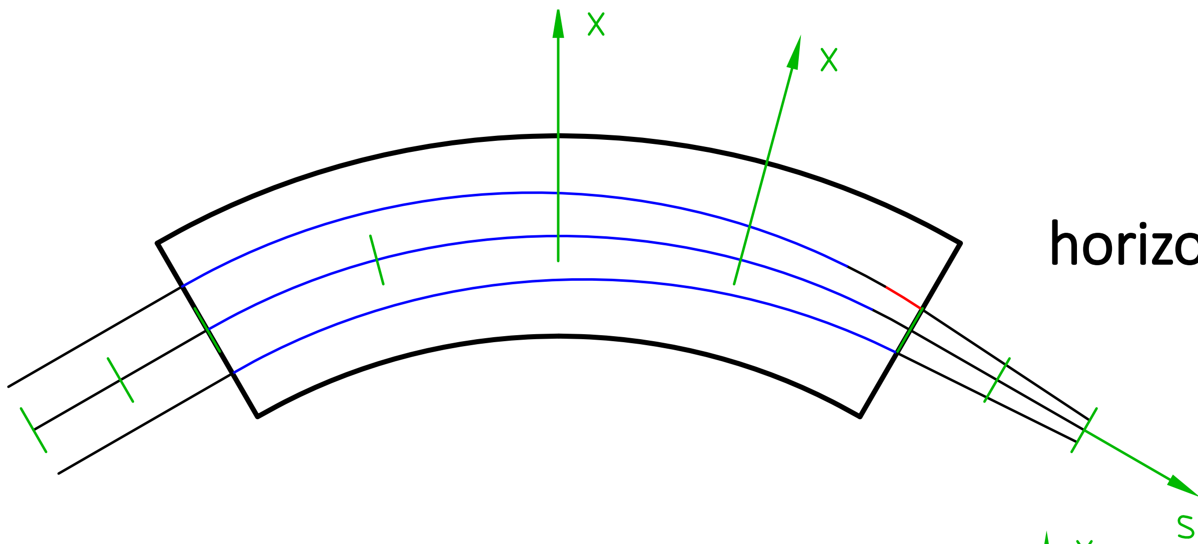


SESAME dipole

Usually two dipole elements are found in lattice codes: the sector dipole (SBEND) and the parallel faces dipole (RBEND)

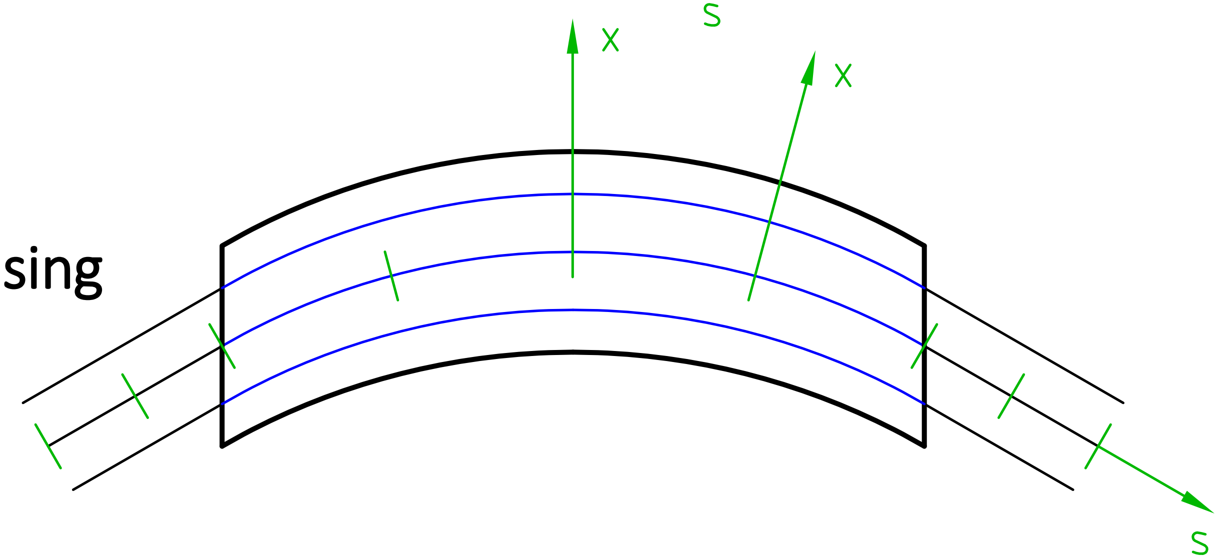


The two types of dipoles are slightly different in terms of focusing, for a geometric effect



SBEND
horizontal focusing

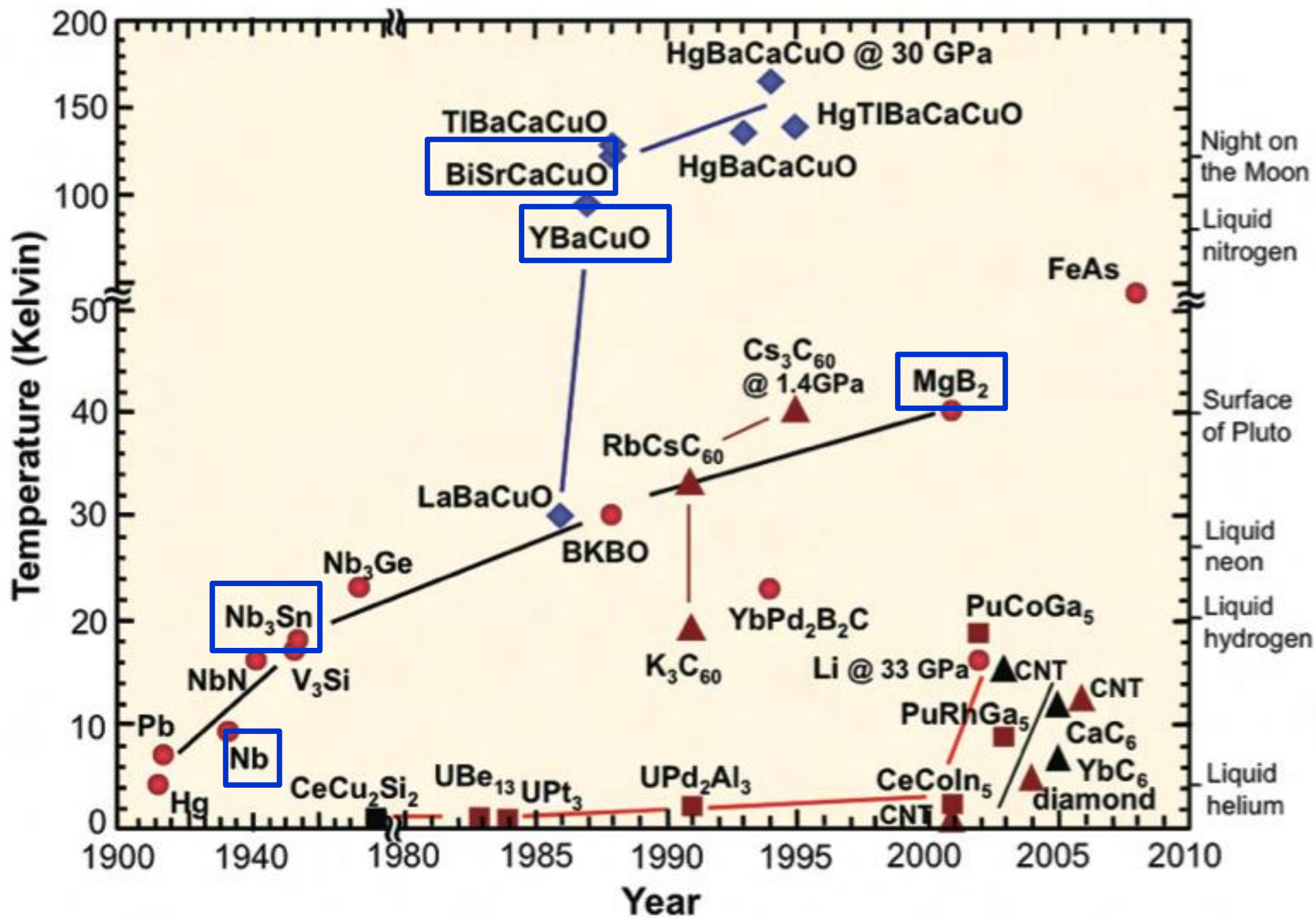
RBEND
vertical edge focusing



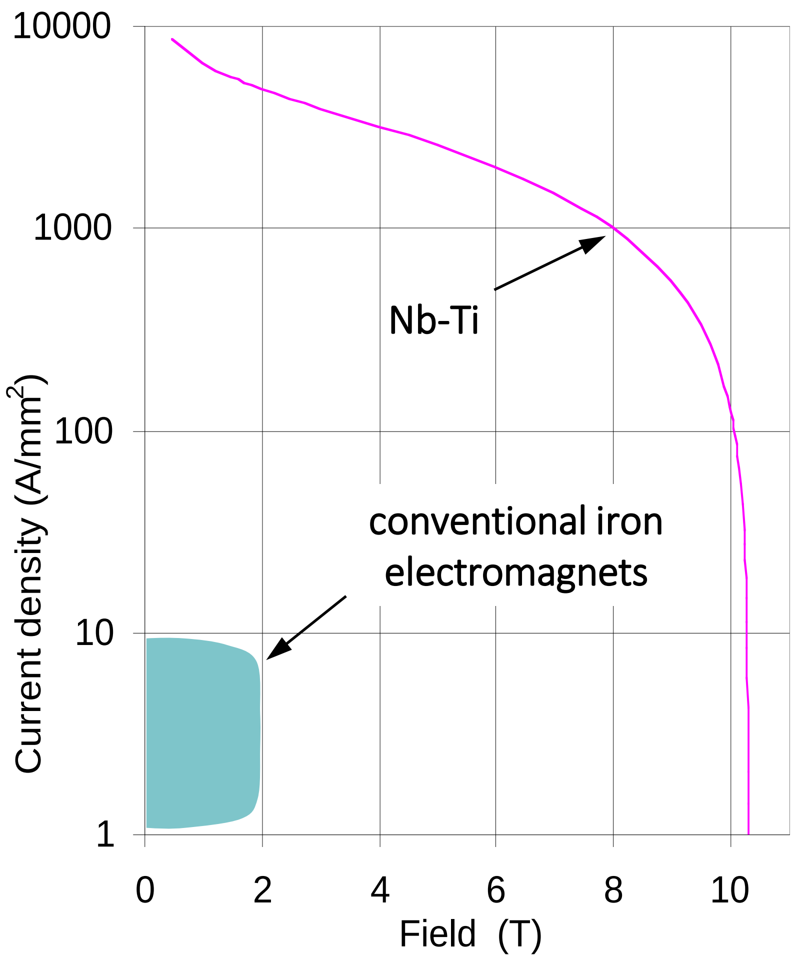
- and anything in between (playing with the edge angles) -

1. Introduction, jargon, general concepts and formulae
2. Resistive magnets
3. Superconducting magnets (thanks to Luca Bottura for the material of many slides)
4. Tutorial with OPERA-2D

This is a history chart of superconductors, starting with Hg all the way to HTS (High Temperature Superconductors)



Superconductivity makes possible large accelerators with fields well above 2 T



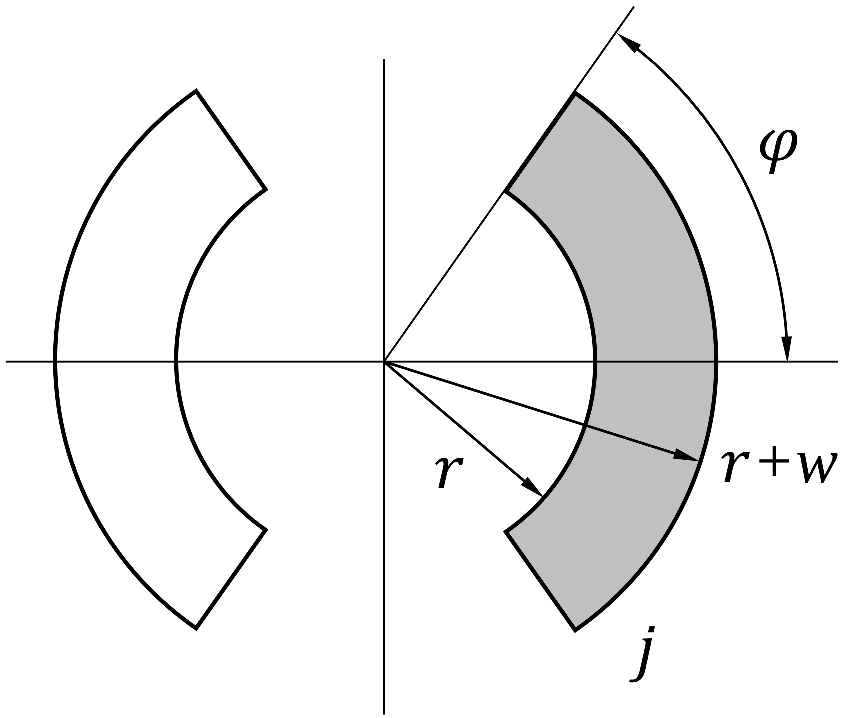
This is a summary of (somehow) practical superconductors

	LTS			HTS		
material	Nb-Ti	Nb_3Sn	MgB_2	REBCO	SCCO	Fe based
year of discovery	1961	1954	2001	1987	1988	2008
T_c [K]	9.2	18.2	39	≈93	95 / 108	up to 58
B_{c2} [T]	≈14.5	≈30	>30	120…250	≈200	>100

The field in the aperture of a superconducting dipole can be derived using Biot-Savart law (in 2D)

$$B_\theta = \frac{\mu_0 I}{2\pi\rho}$$

Biot-Savart law for an infinite wire



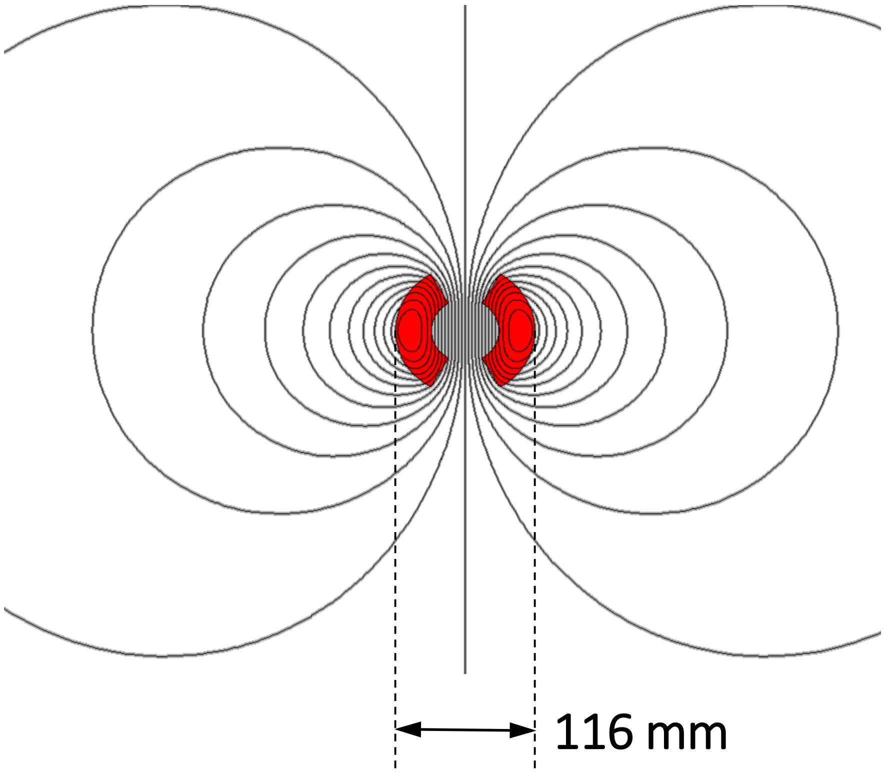
$$B = \frac{2\mu_0 \sin\varphi}{\pi} jw$$

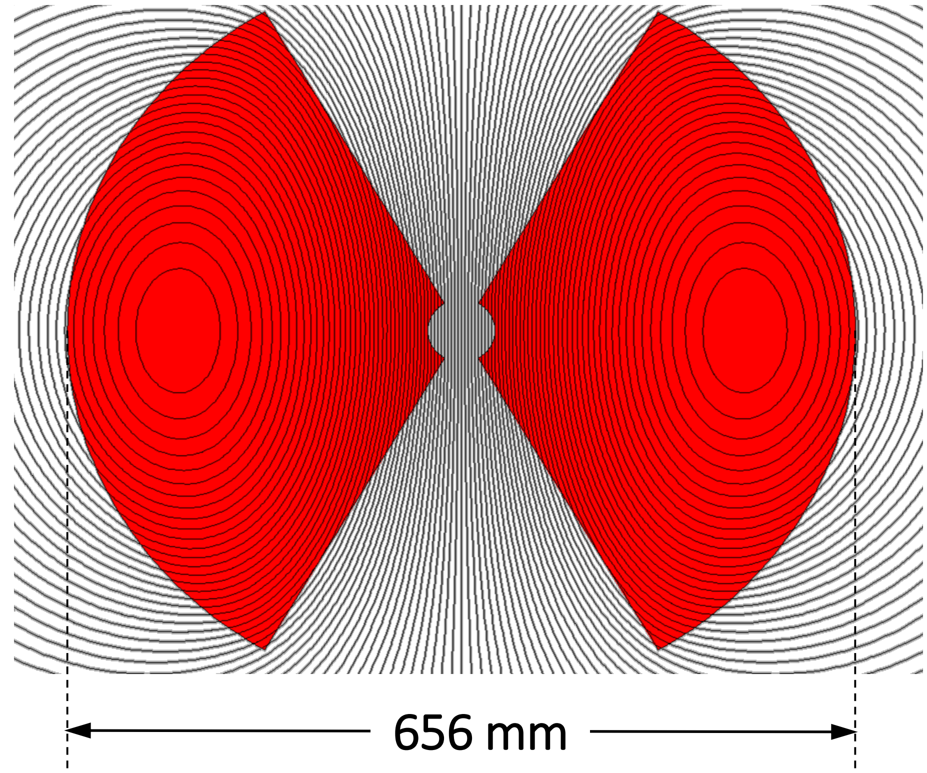
for a sector coil

$$B = \frac{\sqrt{3}\mu_0}{\pi} jw$$

for a 60 deg sector coil

This is how it would look like one aperture of the LHC dipoles at 8.3 T, with two different current densities (without iron)

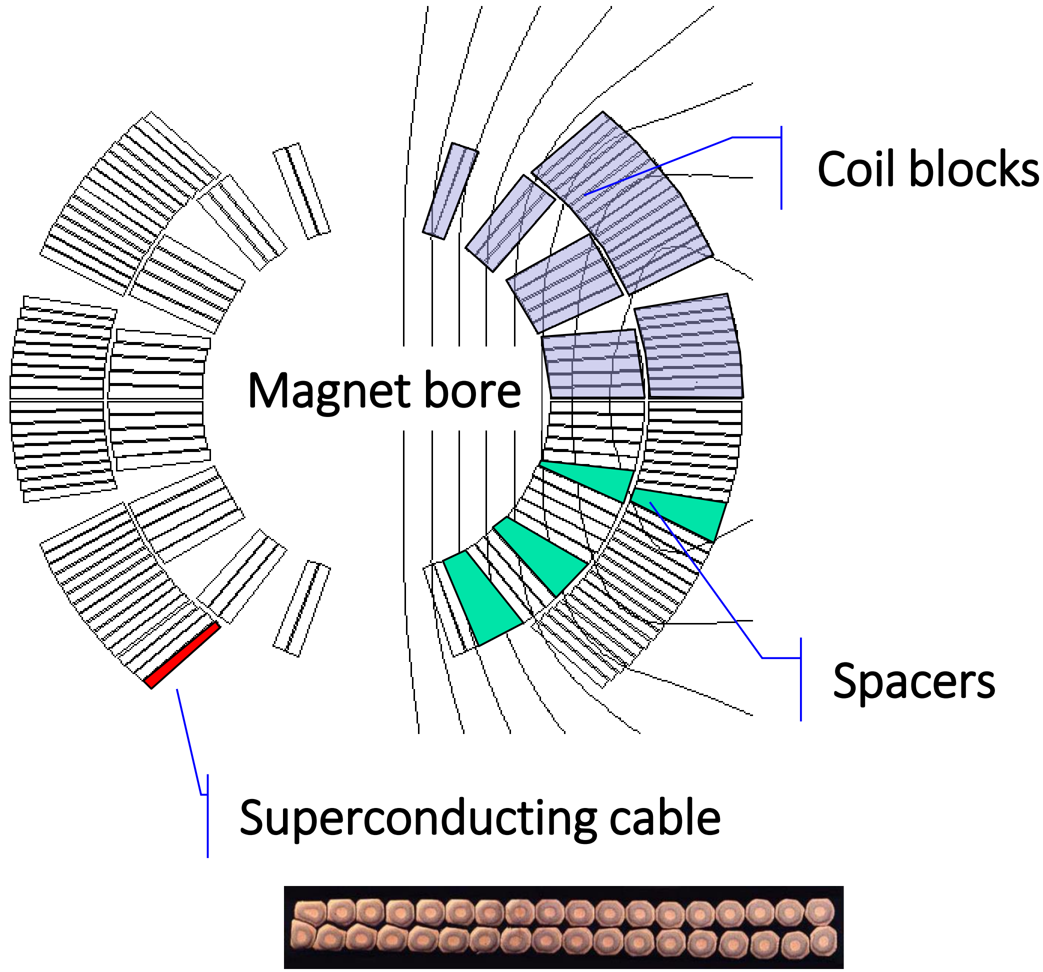




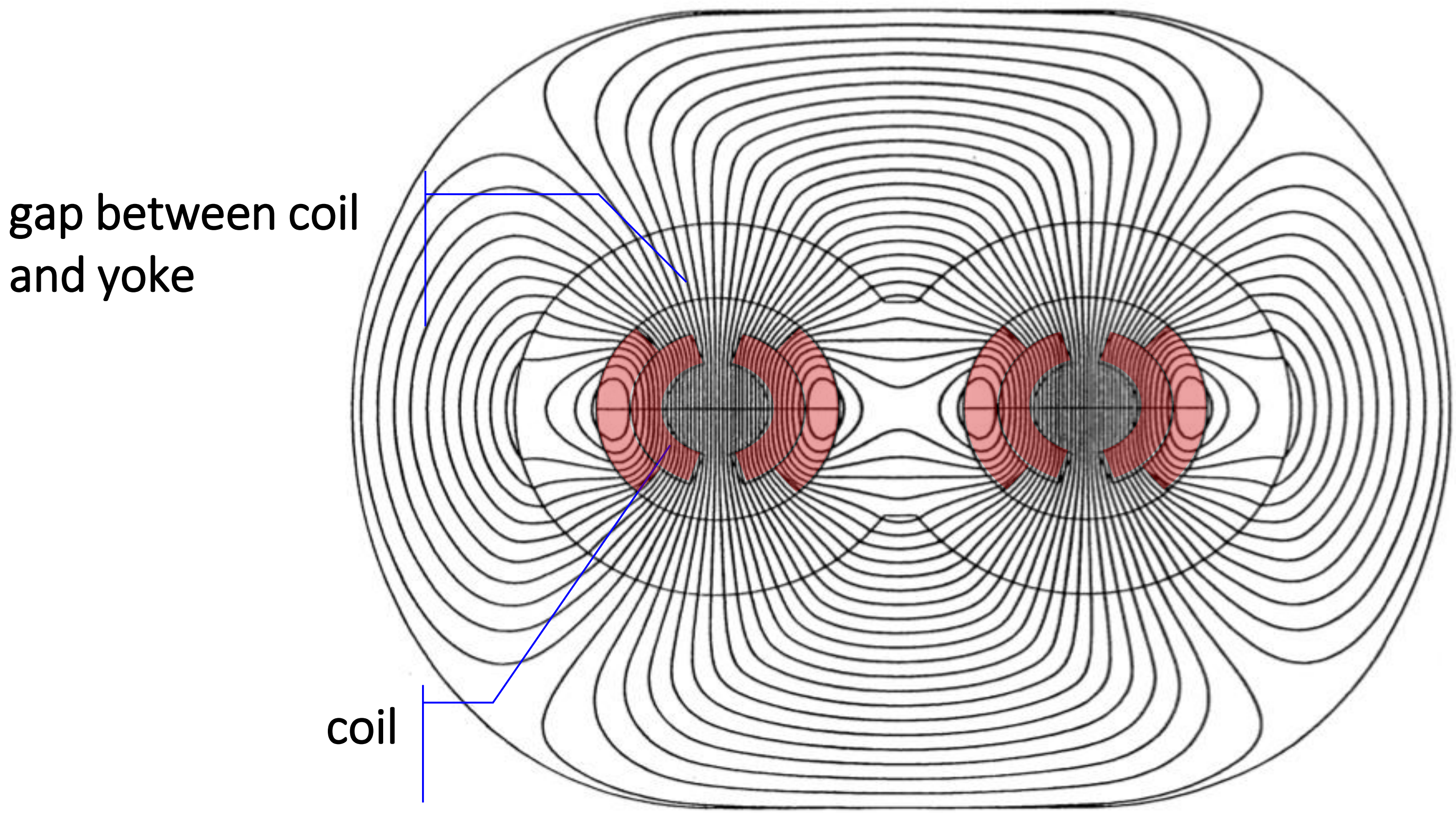
j = 400 A/mm^2
w = 30 mm
NI = 1.2 MA
P = 14.9 MW/m (if Cu at room temp.)

j = 40 A/mm^2
w = 300 mm
NI = 4.5 MA
P = 6.2 MW/m (if Cu at room temp.)

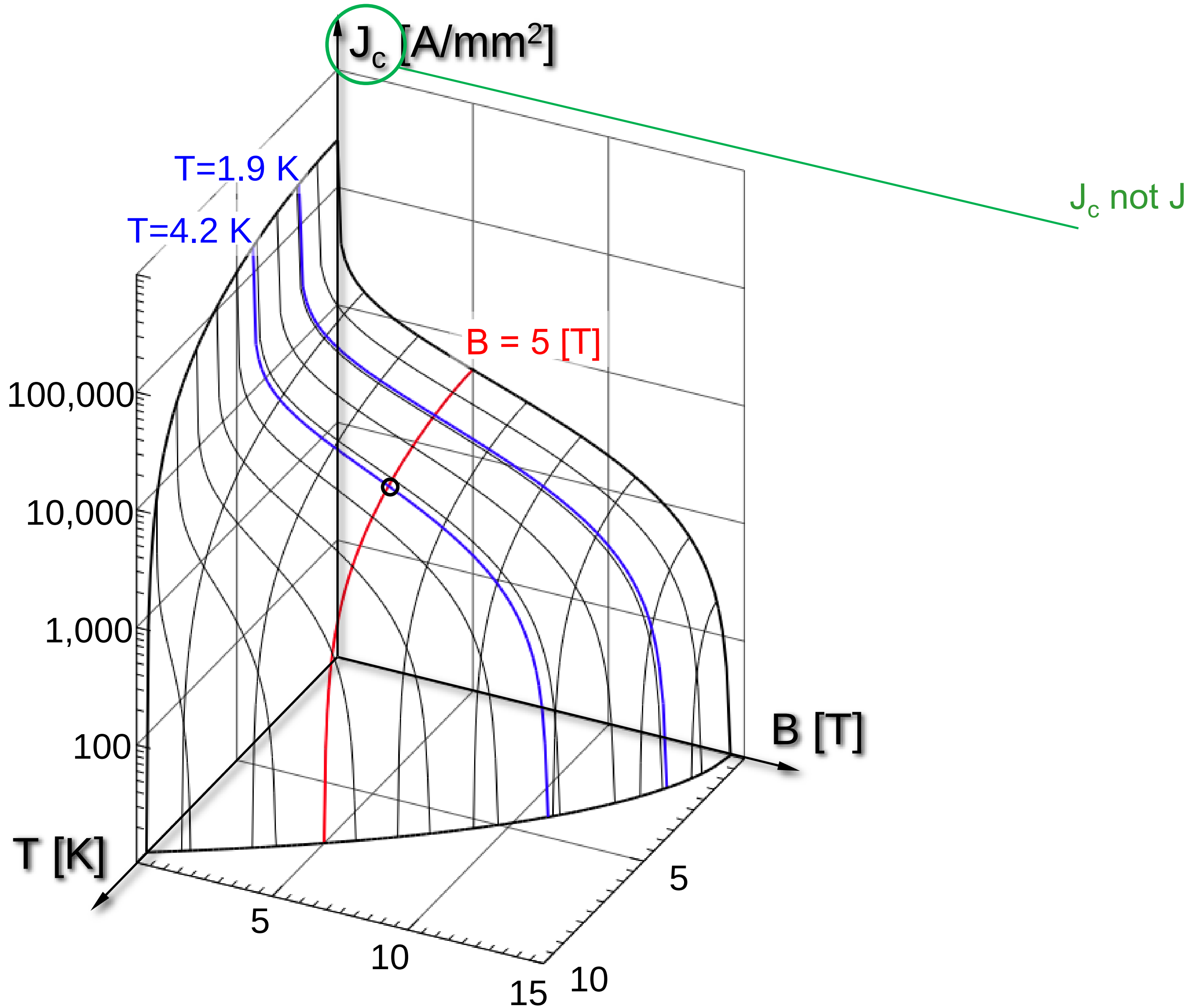
This is the actual coil of the LHC main dipoles (one aperture), showing the position of the superconducting cables



Around the coils, iron is used to close the magnetic circuit

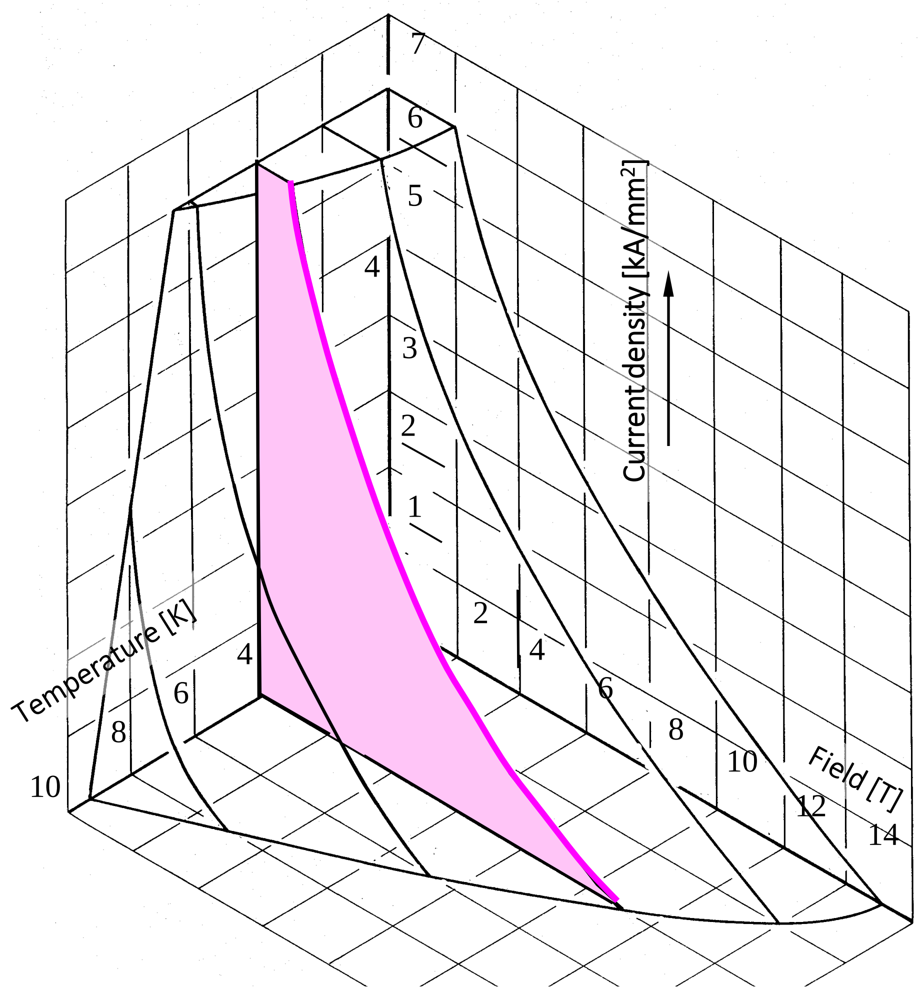


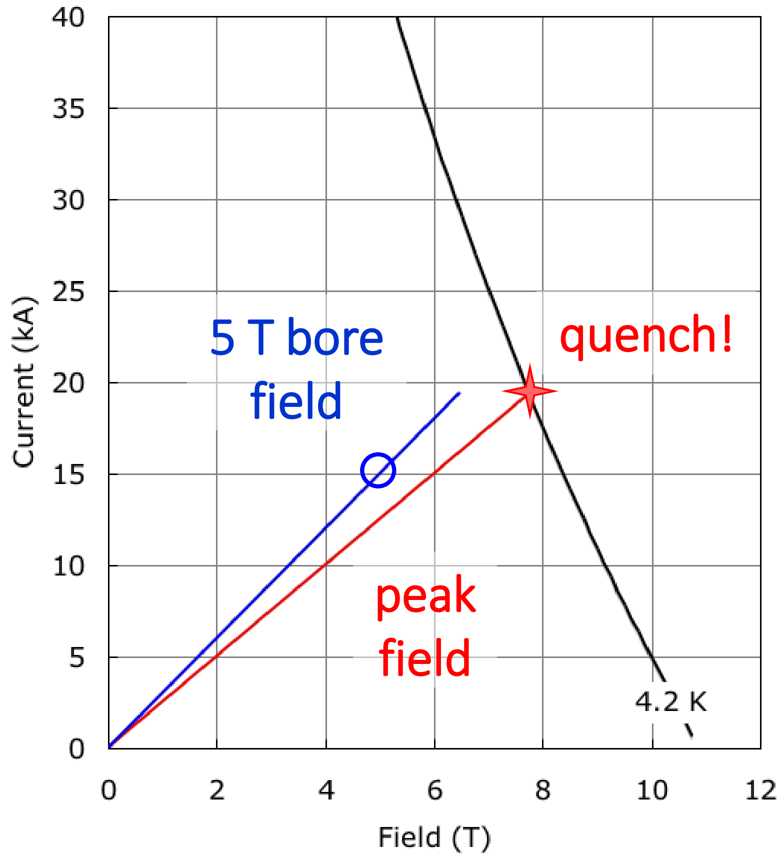
The allowable current density is high – though finite – and it depends on the temperature and the field



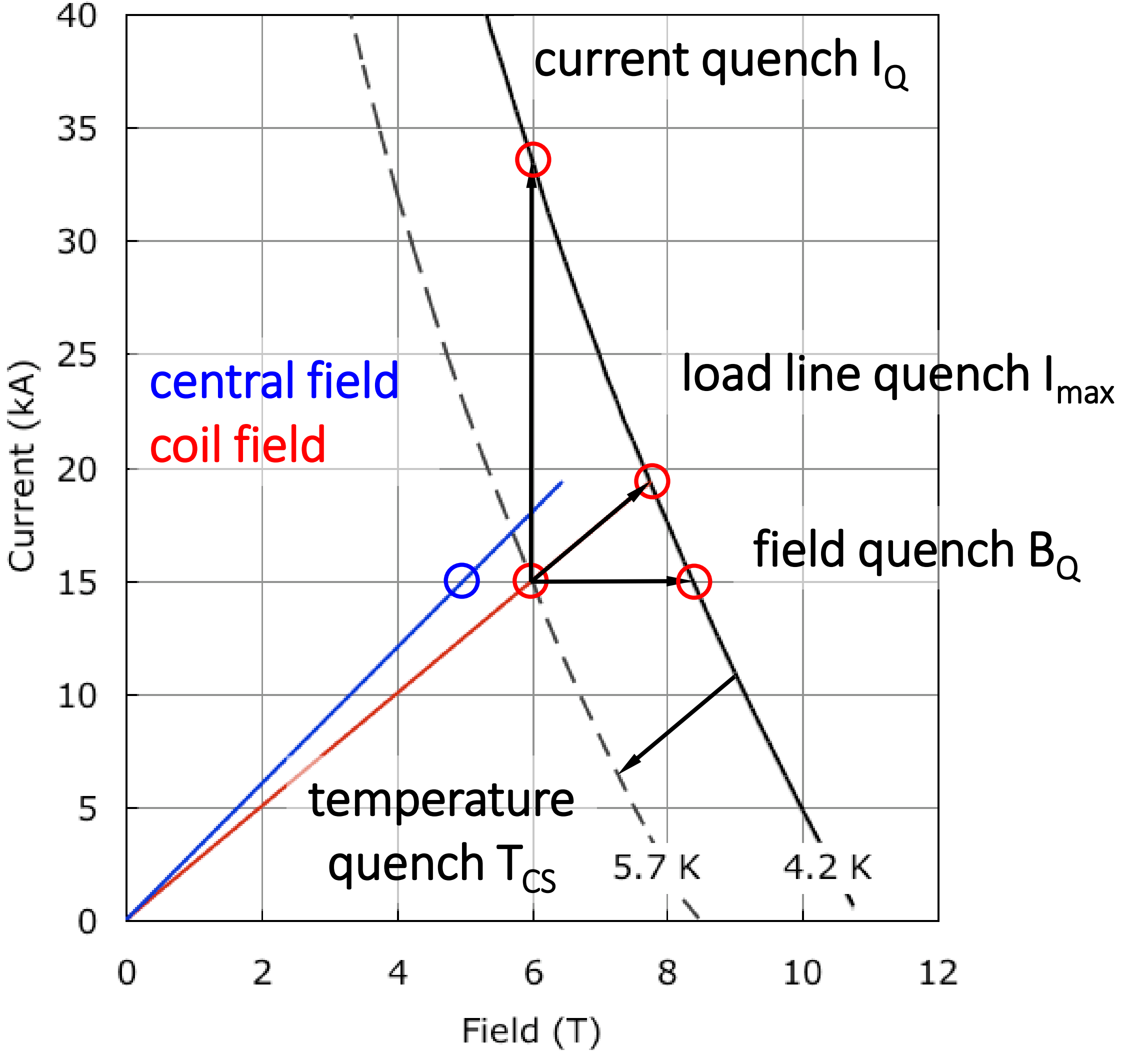
The maximum achievable field (on paper) depends on the amount of conductor and on the superconductor's critical line

Nb-Ti critical surface —— $I_C = J_C \times A_{SC}$ ——→ Nb-Ti critical current I_C (B)



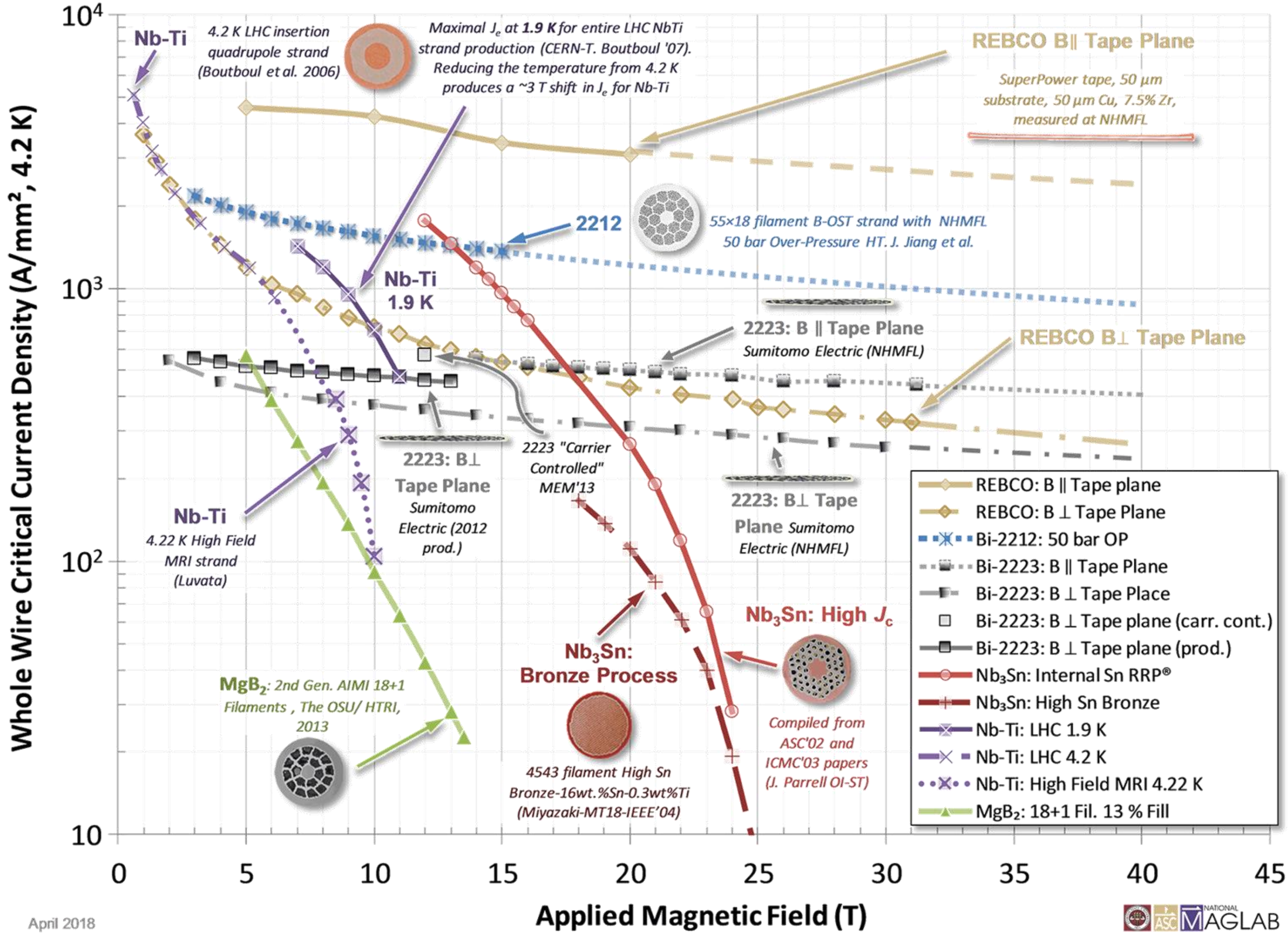


In practical operation, margins are needed with respect to this short sample limit

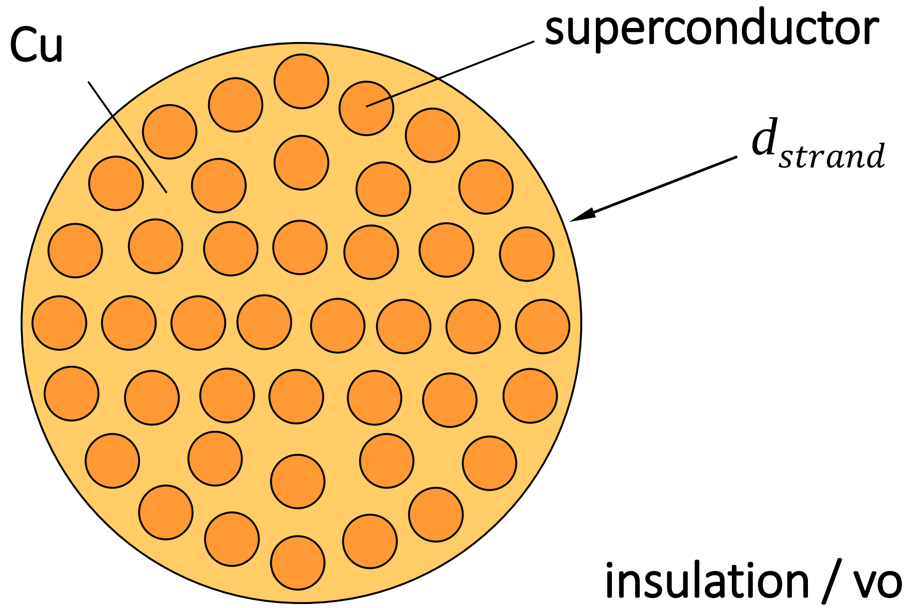


This is the best (Apr. 2018) critical current for several superconductors

Applied Superconductivity Center at NHMFL



The overall current density is lower than the current density on the superconductor

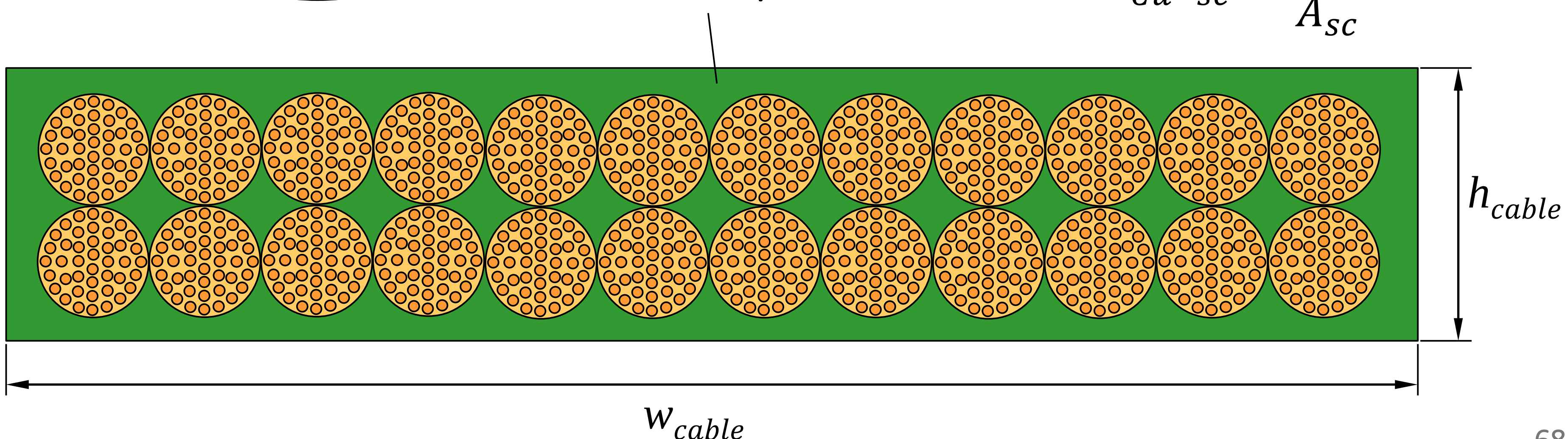


$$j_{overall} = \frac{I}{w_{cable} t_{cable}}$$

$$j_{cond} = \frac{I}{N_{strand} \frac{\pi d_{strand}^2}{4}}$$

$$j_{sc} = (1 + \upsilon_{Cu-sc}) j_{cond}$$

$$\upsilon_{Cu-sc} = \frac{A_{Cu}}{A_{sc}}$$



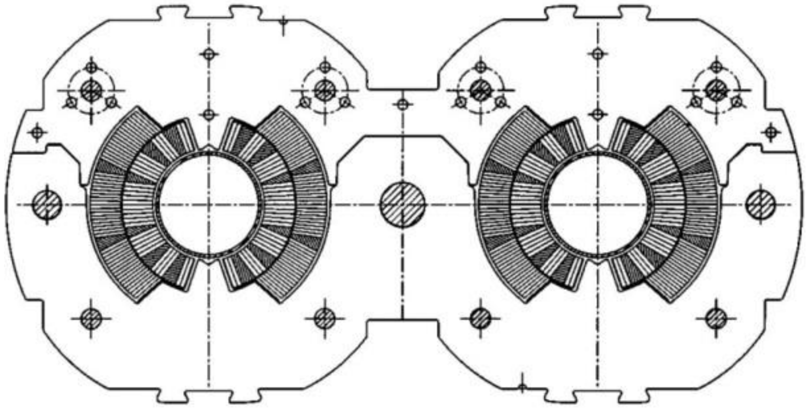
The forces can be very large, so the mechanical design is important

Nb-Ti LHC MB @ 8.3 T

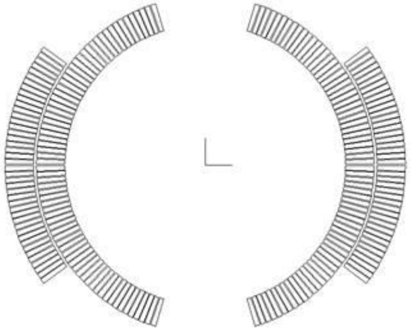
$F_x \approx 350$ t per meter

precision of coil positioning: 20-50 µm

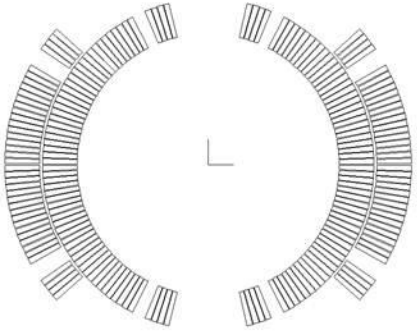
$F_z \approx 40$ t



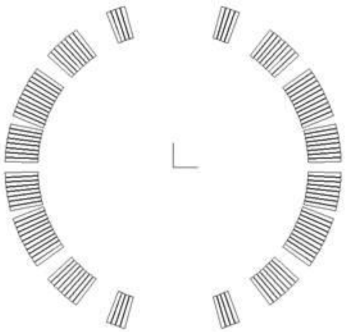
The coil cross sections of several superconducting dipoles show a certain evolution; all were (are) based on Nb-Ti



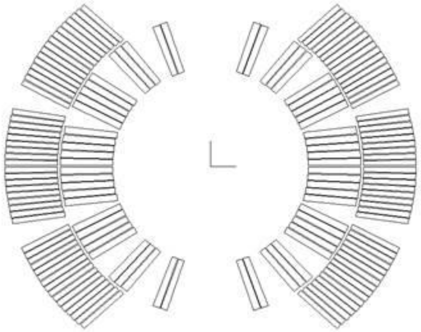
Tevatron



HERA

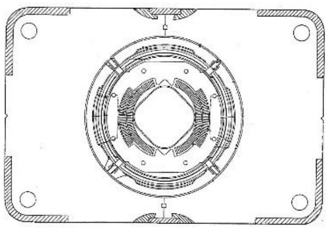


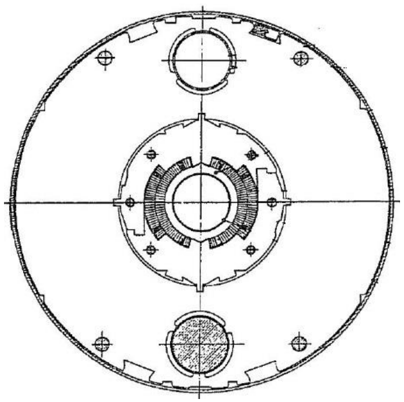
RHIC

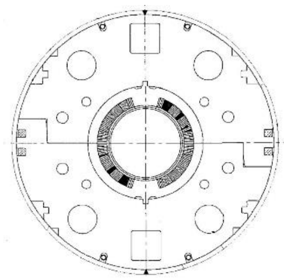


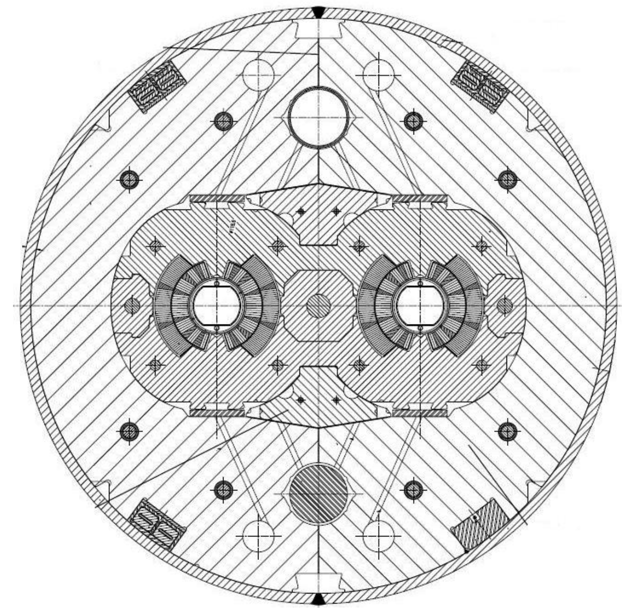
LHC
(one aperture)

Also the iron, the mechanical structure and the operating temperature can be quite diverse









Tevatron	HERA	RHIC	LHC
76 mm bore	75 mm bore	80 mm bore	56 mm bore
B = 4.3 T	B = 5.0 T	B = 3.5 T	B = 8.3 T
T = 4.2 K	T = 4.5 K	T = 4.3-4.6 K	T = 1.9 K
first beam 1983	first beam 1991	first beam 2000	first beam 2008

This is how they look in their machines

Tevatron @ FNAL
(Chicago, IL, USA)

RHIC @ BNL
(Upton, NY, USA)

HERA @ DESY
(Hamburg, D)

LHC @ CERN
(Geneva, CH/FR)

1. Introduction, jargon, general concepts and formulae
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As an example, we will do a simplified 2D model of D1, a large aperture (150 mm) medium field (5.6 T) Nb-Ti dipole, for HL-LHC at CERN

There are different programs used for magnetic simulations

1. OPERA-2D and OPERA-3D, by ~~COBHAM~~ Dassault Systèmes
2. ROXIE, by CERN
3. POISSON, by Los Alamos
4. FEMM
5. RADIA, by ESRF
6. ANSYS
7. Mermaid, by BINP
8. COMSOL

Here are a few references for D1

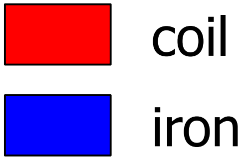
1. K. Suzuki *et al*., Quench protection heater study with the 2-m model magnet of beam separation dipole for the HL-LHC upgrade, MT25 conference, 2017

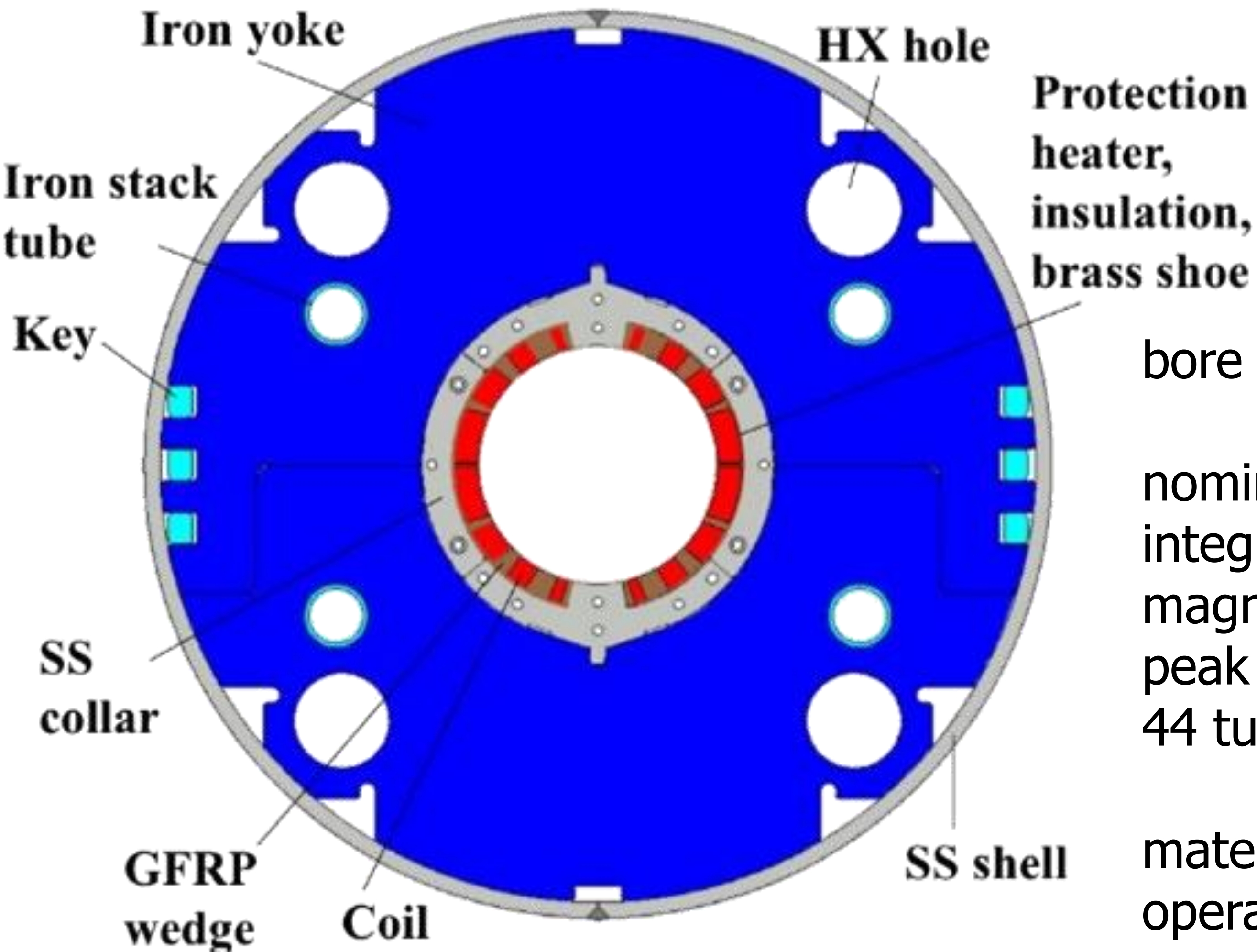
2. S. Enomoto *et al*., Field measurement to evaluate iron saturation and coil end effects in a modified model magnet of beam separation dipole for the HL-LHC upgrade, MT25 conference, 2017

3. M. Sugano *et al*., Fabrication and test results of the first 2 m model magnet of beam separation dipole for the HL-LHC upgrade, ASC conference, 2016

4. S. Enomoto *et al*., Magnetic field measurement of 2-m-long model of beam separation dipole for the HL-LHC upgrade, ASC conference, 2016

D1 is a large aperture dipole, to be installed in the high luminosity insertions of HL-LHC as first dipole(s) after the collision point (recombination dipole)



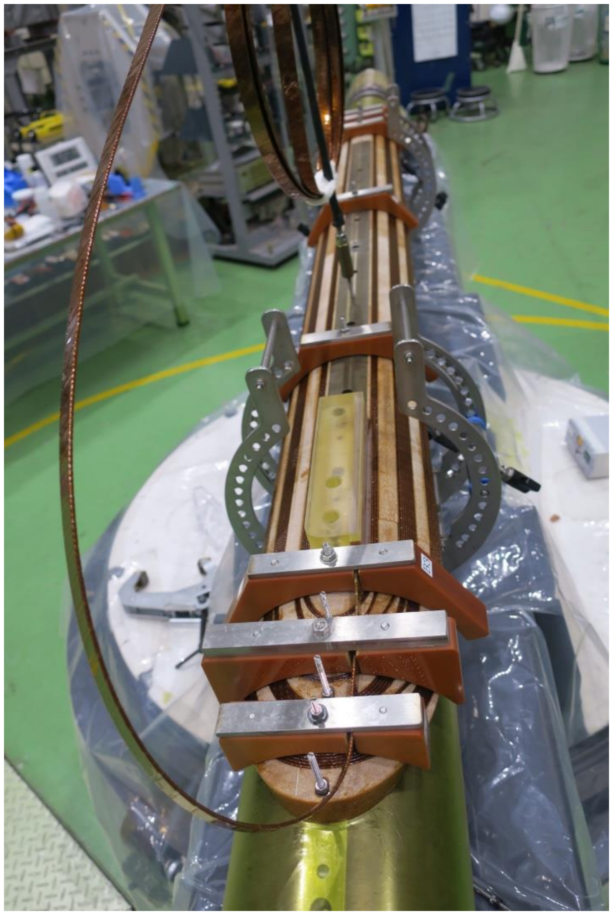


bore diameter 150 mm

nominal field 5.58 T
integrated field 35 Tm
magnetic length 6.27 m
peak field in coil 6.6 T
44 turns per pole

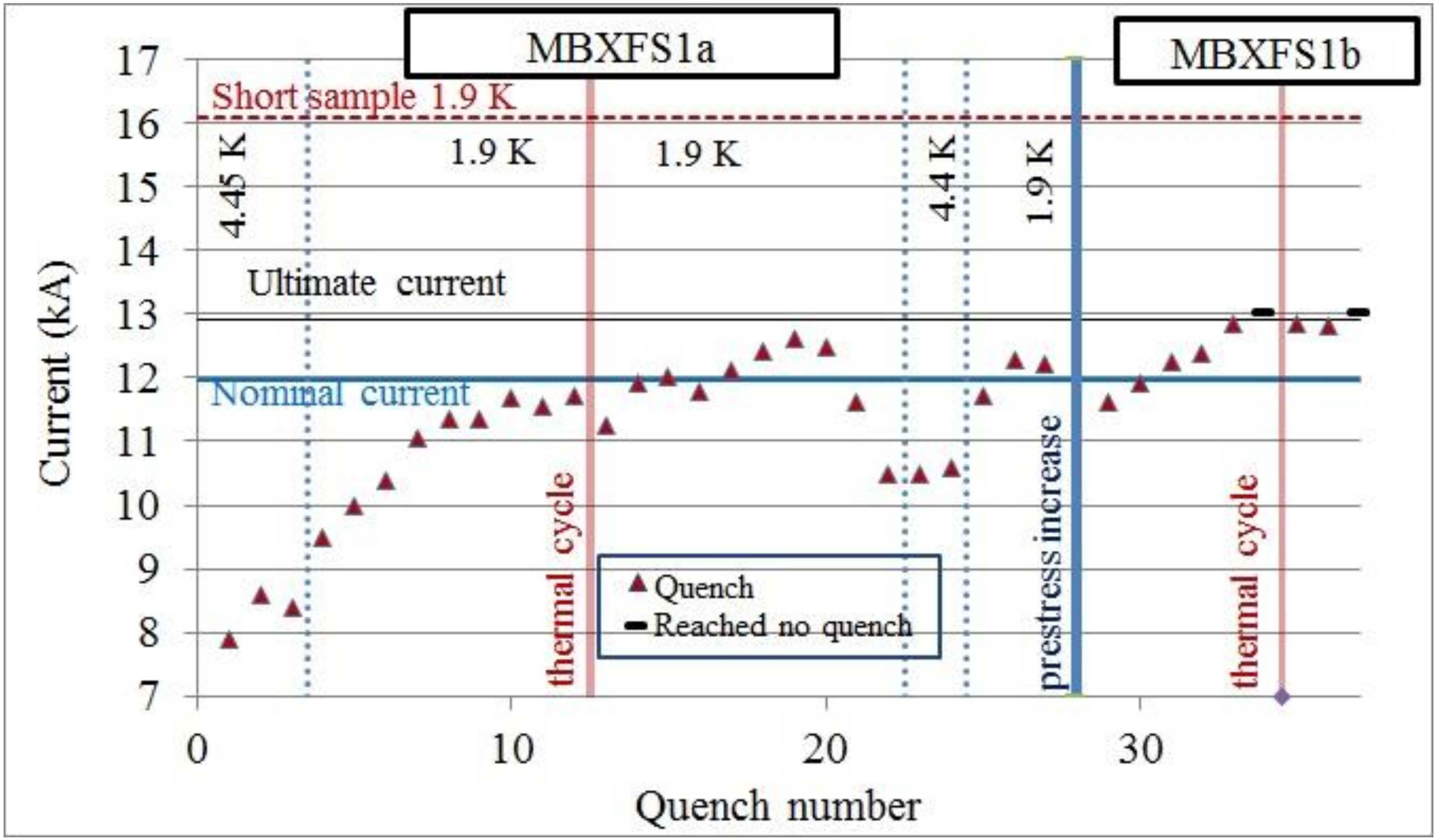
material Nb-Ti
operating temperature 1.9 K
load line margin 76%

This is the winding of a coil for the second short model (left) and the disassembly of the first short model (right)



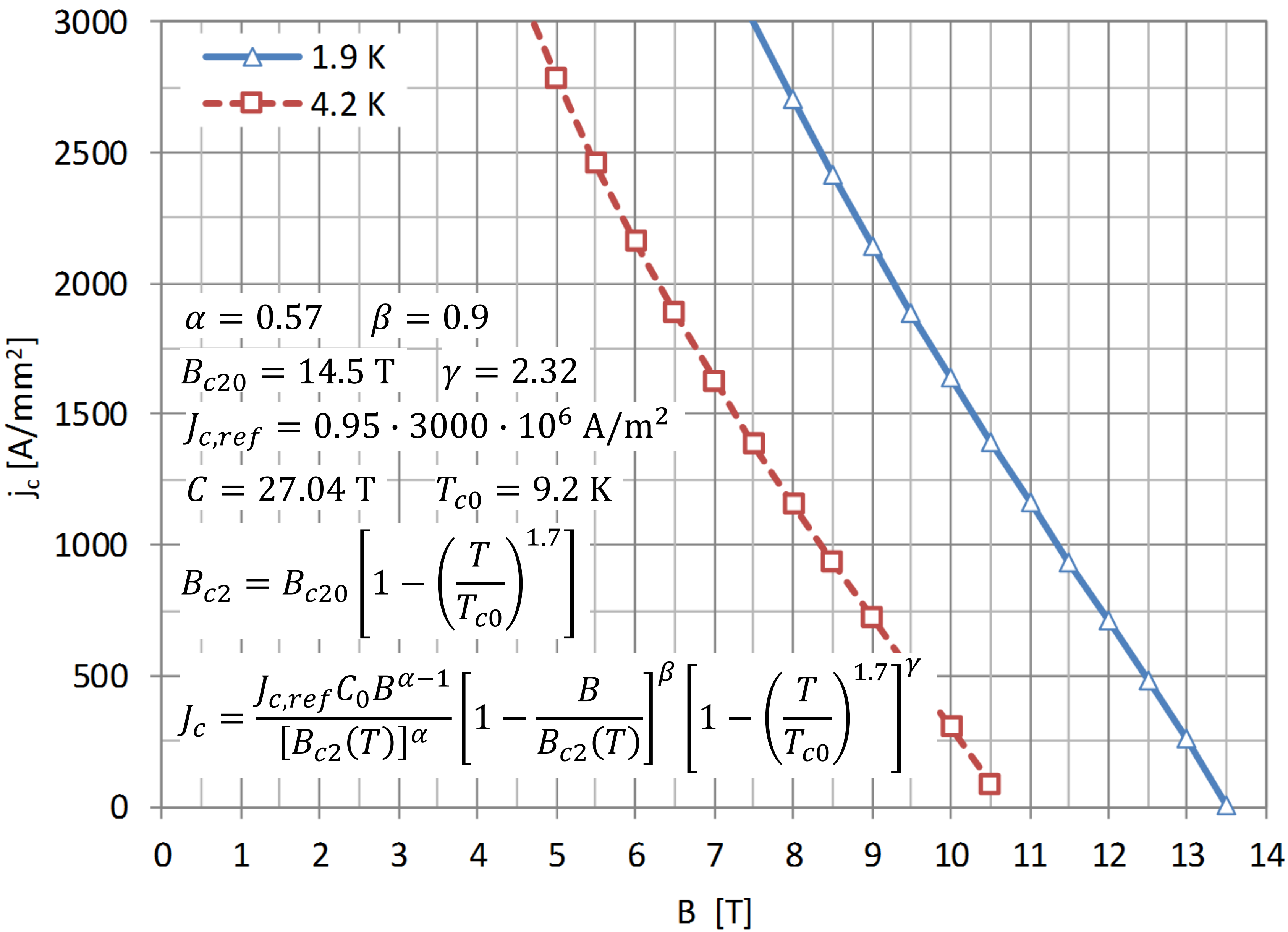
courtesy of KEK

This is a training curve for a D1 model – one of the moment of truth for a superconducting magnet

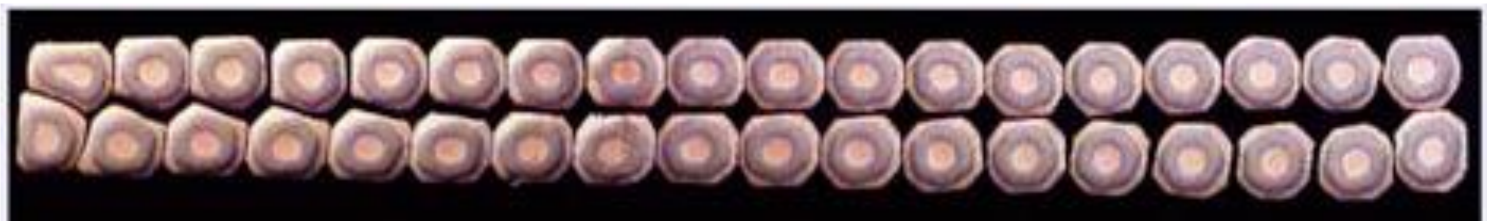


courtesy of KEK

For our exercise, we assume the following critical curve for the Nb-Ti conductor of D1



With the geometry of the cable and the nominal current, we can then compute the current densities for D1



$$A_{cable} = 26.0859\ \text{mm}^2$$

$$N_{str} = 36 \qquad d_{str} = 0.825\ \text{mm} \qquad \nu_{\text{Cu-sc}} = 1.9$$

$$I = 12047\ \text{A}$$

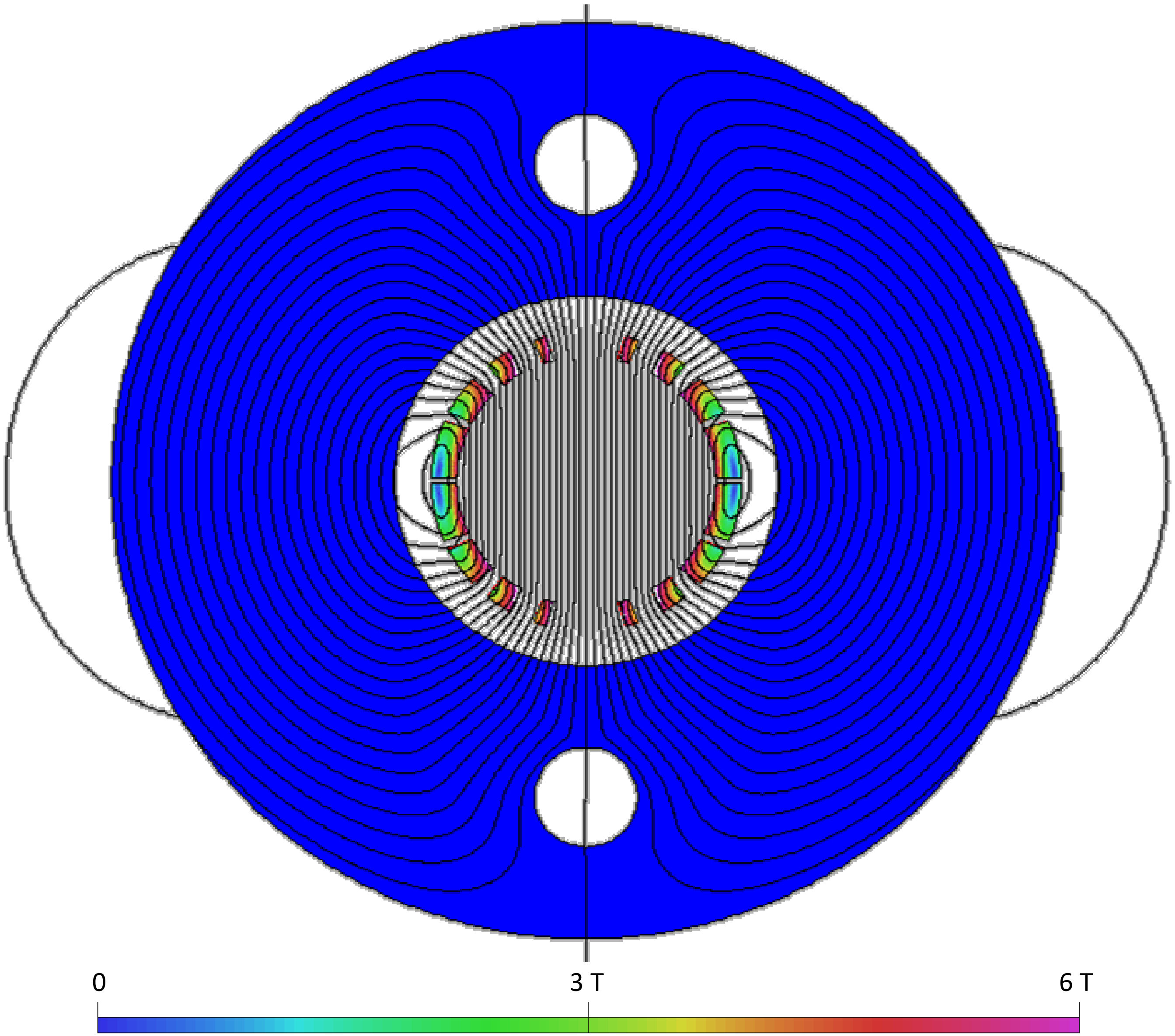
$$J_{\text{ovr}} = \frac{I}{A_{cable}} = 461.8\ \text{A/mm}^2$$

$$J_{\text{cond}} = \frac{I}{N_{str}\frac{\pi d_{str}^2}{4}} = 626.0\ \text{A/mm}^2$$

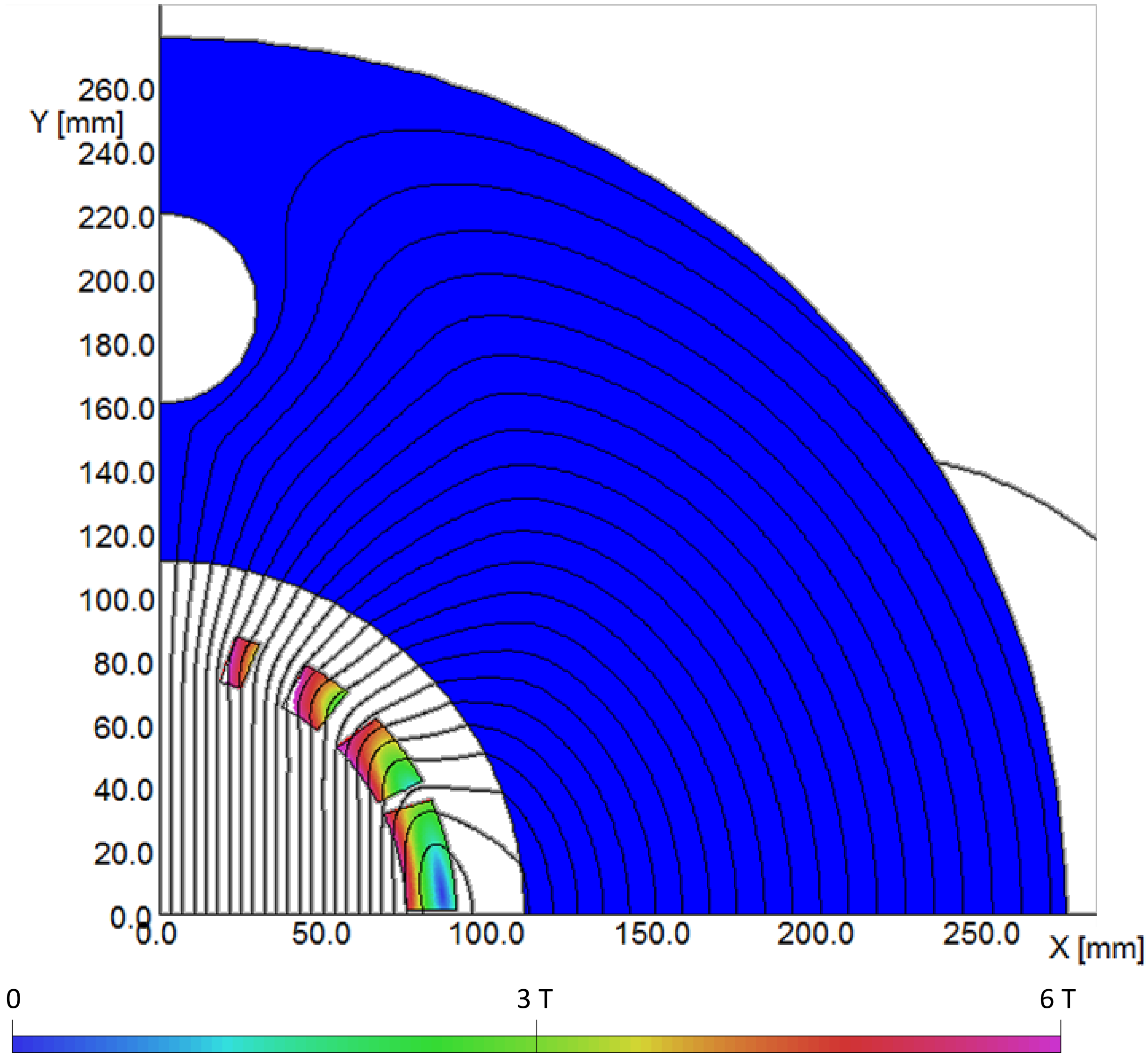
$$J_{\text{sc}} = (1 + \nu_{\text{Cu-sc}})\, J_{cond} = 1815.4\ \text{A/mm}^2$$

× 3.9

Here are the field and flux lines as computed in 2D with our (simplified) OPERA model, for the nominal current of 12047 A



Considering the symmetries, only one quarter of the dipole can be modeled; here we plot in particular the field in the coil

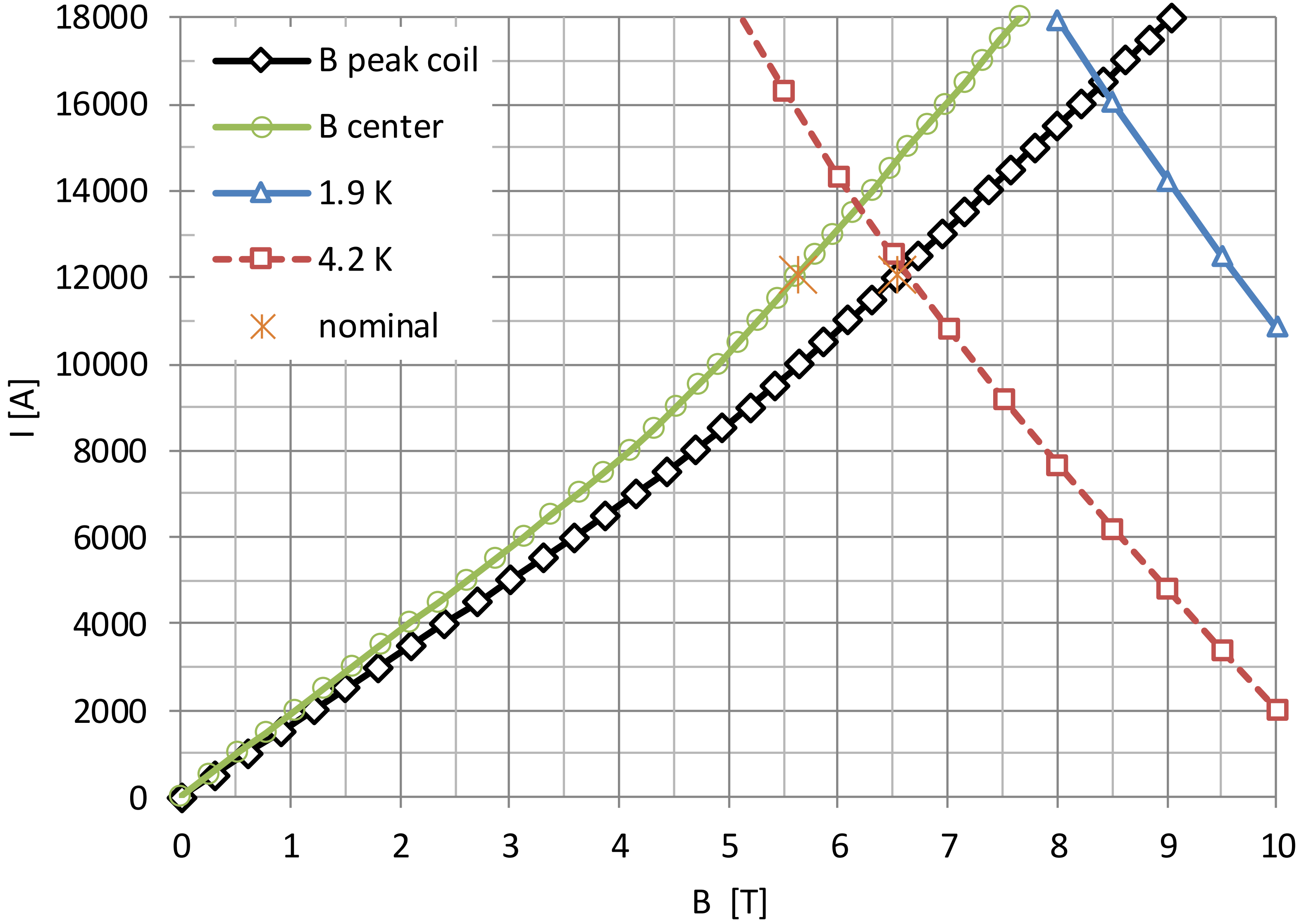


B_{center} = 5.63 T

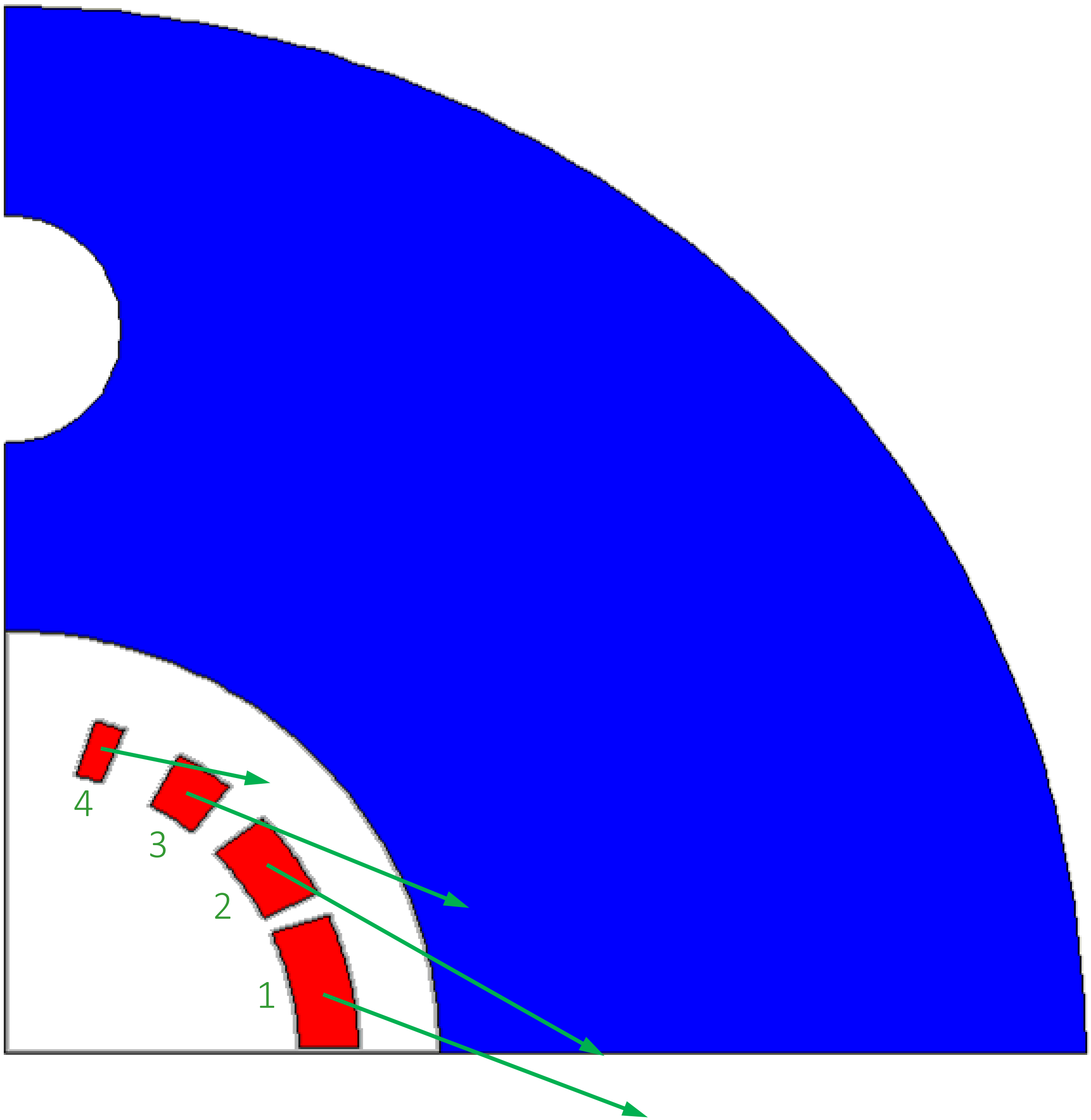
B_{peak} = 6.54 T

I_{nom} = 12047 A

This is the “load line” of D1 using our 2D model



The Lorentz forces can be quite impressive



block 1
$F_x = 0.452$ MN/m
$F_y = -0.171$ MN/m

block 2
$F_x = 0.470$ MN/m
$F_y = -0.266$ MN/m

block 3
$F_x = 0.394$ MN/m
$F_y = -0.159$ MN/m

block 4
$F_x = 0.236$ MN/m
$F_y = -0.048$ MN/m

in total (per quarter)
$F_x = 1.551$ MN/m
$F_y = 0.645$ MN/m

To complete the 2D analysis, these are the allowed multipoles, computed with our model

		I = 600 A	I = 6000 A	I = 12047 A
B_1	[T]	0.31	3.13	5.63
b_1	[1e-4]	10000	10000	10000
b_3	[1e-4]	-22.4	-17.9	0.3
b_5	[1e-4]	3.7	3.0	-1.6
b_7	[1e-4]	-1.9	-1.8	-3.0
b_9	[1e-4]	0.1	0.1	0.0
b_{11}	[1e-4]	-0.0	0.0	0.1

R_{ref} = 50 mm

Here are a few magnet references for your project – that is, dipoles for a scSPS

1. A. Kovalenko, "6 T Dipole for the SPS Upgrade," FCC week, 2017

2. A. Kovalenko, "6 T Pulsed Dipole for the SPS Upgrade," FCC week, 2018

3. J. Kaugerts *et al.*, "Design of a 6 T, 1 T/s fast-ramping Synchrotron magnet for GSI's planned SIS 300 accelerator," IEEE Trans. Appl. Superc., v. 15, n. 2, Jun. 2005

4. H. Mueller *et al.*, "Next Generation of Fast-Cycled Dipoles for SIS300 Synchrotron," IEEE Trans. Appl. Superc., v. 24, n. 3, Jun. 2014

Proposed steps for your dipole work

1. take the time to do a (limited) literature review, based on the references in the previous slide
2. draft a functional specification, based on the input from the other groups (ex. optics) to define for ex. field and aperture; you can then also list the assumptions about the superconducting material (like J_c fit, operating temperature, amount of stabilizer, load line margin, cable size)
3. you can then sketch a cross section, setting up a 2D magnetic model (one quarter), to decide on the number of turns, their overall position (for field quality, a sector model can be a good approximation), the size of the return yoke, etc.; this is an iterative process; you can adapt the scripts we used for D1
4. at the end, you can write up your report, compiling in particular a table with basic properties of your design